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Application of rotor position sensor fault tolerant control in electric vehicle with PM BLDC motor drives

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Abstract: In order to develop a PM BLDC motor control system, which will be tolerant of selected faults, simulation work was first performed and then verified on a universal test stand. The results were published in earlier works. The next stage of works was the implementation of previously developed algorithms on the target research test stand – in this case, the prototype vehicle. This last stage of the laboratory work has been presented in this article, i.e. it has been presented the results of experimental research related to the reproduction of rotor angle position, used after the detection of a rotor position sensor fault. A new test stand with the laboratory prototype of a vehicle with two PM BLDC motors is presented. A zeroth-order algorithm (ZOA) was used as a fault compensation method. The effectiveness and usefulness of the previously proposed methods have been confirmed.

Key words: PM BLDC motor, Hall effect sensor, fault tolerant drive, ZOA, electric vehicle

1. Introduction

One of commonly used types of electrical motors are Permanent Magnet Brushless Direct Current Motors (PM BLDC motor). A characteristic feature of their construction is the elimination of a mechanical commutator, the role of which was taken over by a power electronic system. However, to operate correctly it requires the information on rotor position which can be obtained in a number of ways. The two most popular ones are: digital rotor position sensors (optical and Hall effect ones) and sensorless methods based on the electromotive force or motor interphase voltages. Other less popular approaches encompass: a standard incremental encoder with appropriate software, an absolute or commutation encoder (with UVW signals). Each of these solutions has its specific characteristics. For instance, discrete rotor position sensors are more frequently used when there is a need for a high starting torque and sensorless methods could be inefficient, however, they are hardly ever used in high-speed PM BLDC motors in which the distribution and hysteresis of these sensors can significantly influence their correct operation. The use of sensors (Hall effect or optical ones) facilitates the development of the control system, however, on the other hand, it means the use of additional elements whose incorrect operation significantly influences the operation of a drive and, potentially, can decrease its reliability. The specificity of the applications of PM BLDC motors in vehicle drives requires them to be highly resistant to faults. Hence the current research trends are related to the search for the methods which would allow for quick detection and compensation of various faults occurring in in these drives. The paper focuses on the description of drive operation during the compensation of a rotor position sensor fault in which the sensor is damaged permanently resulting in a constant input value. This problem is indicated by, among others, the users of electrically-assisted bicycles in which such a fault is quite frequent due to the conditions of their operation. The earlier research [1] showed that operation with a faulty rotor position sensor causes phase currents deformations, vibrations, noise and higher energy consumption. Additionally problems with restart and reversal may occur.

For the purpose of ensuring safe and fault tolerant drive operation, its control system should perform additional tasks: the detection and identification of faults on the basis of selected symptoms, isolation of a faulty element and compensation actions (software or hardware related). The detection and identification of rotor position sensor faults can be conducted on the basis of the symptoms determined by values based on phase currents and voltages [2] or also directly on signals from rotor position sensors [3–5]. The next stage is the isolation of a fault and its compensation. Here, it is possible to reject the signal from a faulty sensor while preserving other signals from healthy sensors and to generate the missing information or to obtain the information about rotor position from another source. In the development and selection of the available methods of detection, identification and compensation methods, one should pay attention to those which require a small number of additional physical or software related elements and are computationally simple. Thanks to this, the effect of tolerance to a given fault can be achieved using a simple and quick solution.

In this paper the operation of the PM BLDC motor drive during the fault occurrence of a rotor position sensor fault has been described. Fault tolerance provides three main steps: detection (identification) of a fault, isolation and compensation.

The detection and identification of faults was based on signals generated by rotor position sensors [3]. The method is described in [4, 6], additionally, the necessary direction signal of rotational speed and its value were determined in an indirect way on the basis of rotor position sensors due to operation mode without an incremental encoder in the setup.

Another action, after the detection and identification of a faulty sensor, is hardware or software reconfiguration to ensure fault tolerant operation of rotor position sensors. This issue has relatively rich bibliography. Control resistant to this type of fault requires the evaluation of existing solutions and the selection of those which will ensure the correct operation of a vehicle, in accordance with the adopted assumptions, with necessary modifications. It is possible to distinguish the following solutions which can be used when it is necessary to compensate the faults of a rotor position sensor:

- reconstruction of rotor position using sensorless methods (software), with the help of available measurements and motor parameters (observers, estimators, including the Kalman filter and neural networks), VTO [3, 7–9],
- software generation of the missing signal on the basis of two correct pieces of information about the transition time between particular states (ZOA, an algorithm using FPGA) [3, 5],

- determination of commutation torques using additional hardware systems (e.g. comparators) with possible compensation for delay time in methods based on voltage signals or the electromotive force [6, 10],
- use of an incremental or absolute encoder [11].

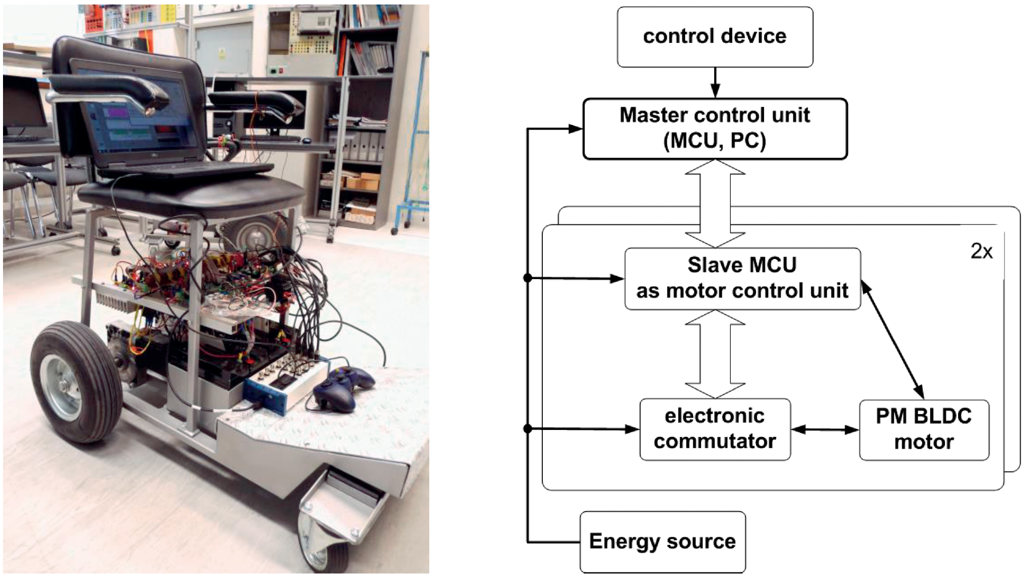
The choice of one of the above compensation methods requires special attention to checking whether it is tolerant to the faults of power electronic switch (transistors) in the commutator, it should also allow one to start a motor in the halt state and operation in the assumed range of rotational speeds.

Reference research is connected with compensation methods for permanent damages of a rotor position sensor which can determine the missing signal software-wise with the use of the two remaining, efficient sensors – the ZOA method [3]. Hence the identification of a faulty element is extremely important. Contrary to sensorless methods, the information about a fault is not sufficient in this case, as in, e.g. [4, 6]. Another additional step is to isolate the fault. This is to reject the signal from the faulty sensor in the control program.

The research was conducted firstly in an open loop control system to confirm that the rotor position reproduction algorithm was implemented correctly and then in the cascade system of the rotational speed control with the subordinated phase current control loop. The tests were conducted on the laboratory test setup described in [1] and example waveforms obtained during this work stage were presented in [12].

However, the method of ensuring fault tolerance was prepared for use in an electric vehicle. Therefore, a new test bench was prepared and the first results of the test have been presented in this paper. The vehicle shown in Fig. 1(a) has two PM BLDC motors (346 W, 11 A, with built-in speed reducing gearbox – ratio 30:1), each powered by a separate inverter (electronic commutator), controlled by the ARM Cortex-M4 microcontroller (STM32F407 type). The control software has been moved from the DS1103 DSP processor to the slave microcontroller unit (MCU) and the block commutation type has been maintained, in which transistors are conducted in accordance with the rotor position coded by digital sensors. Additionally the top group of transistors perform regulatory functions and can be controlled by a PWM signal. A personally made power electronics part also allows one to carry out researches related to the power transistors faults. The target master control system (which plays the role of user interface) will be based on a microcontroller unit. However, during laboratory tests, for convenient testing of various fault cases, the notebook with master control software (written in C#) was used. A standard game controller (USB joystick, connected with notebook) was used as a control device (see Fig. 1(b)). It was responsible for referencing the speed and trajectory of the vehicle (analog knob) and the digital buttons were responsible for switching the test conditions, like selection which method for fault compensation should be used (if any), and they were also responsible for introducing fault conditions.

The most important part of the control software (sensor readouts, phase current measurements, the determination of rotational speed and transistor control) was carried out with the frequency of the PWM signal. Controller fault states, which are the subject of this research, are generated by the software, without the physical destruction of any elements, by adopting a logical constant instead of the value brought by a given rotor position sensor. The experimental results shown in the next part come from first tests, when the control unit operated in an open loop, still without torque or speed feedback.



(a) (b)

Fig. 1. Mobile test stand: laboratory prototype of electric vehicle with PM BLDC motors (a) and its simpilfied architecture of control system (b)

Previous work [1, 4, 6, 12] focused on the analysis of symptoms and the research for methods to detect and identify faults, as well as their compensation. Simulation and experimental tests were carried out on universal laboratory test stands. These tests have shown that selected faults (e.g. rotor position sensors faults) can be detected and compensated to ensure correct operation of the drive. Therefore, a stand has been prepared in which such tolerance can be highly desirable – a vehicle with an electric drive. This article presents new research results, i.e. studies of previously known algorithms, but implemented on a new research object. In particular, (in relation to work [12]) the type of control system (from the signal processor used in the research and development work to the general purpose microcontroller), the type of electric motor and the type of test stand – from the stationary test bench to the vehicle moving around the laboratory – have been changed.

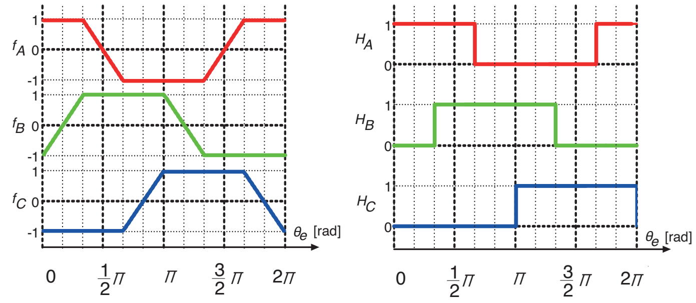
2. ZOA method

A ZOA method (Zeroth Order Algorithm, [3]) to restore information about the rotor position angle after sensor fault occurrence, has been implemented in the slave control unit from prototype, shown in Fig. 1. Even though the method has been described in [12], the explanation will be repeated here for a better understanding of the results.

During the operation of an efficient drive, the rotor position sensors change their states every 60 electrical degrees. Also position P (1), coded using electrical degrees, changes its values along with the angle of rotation in a special order. For a positive speed direction, these will be the following, successive values: $\ldots \rightarrow 4 \rightarrow 6 \rightarrow 2 \rightarrow 3 \rightarrow 1 \rightarrow 5 \rightarrow 4 \rightarrow \ldots$. For a negative speed direction this order is reversed. Among 8 possible values, which can be adopted by signal P, only 6 carry the correct information. The other two indications, i.e. $(H_A, H_B, H_C) = (000)$ or $(H_A, H_B, H_C) = (111)$, i.e. $P = 0$ or $P = 7$ for sensors distributed every 120 electrical degrees, occur only in the faults state of one of the sensors.

$$P = 4H_A + 2H_B + H_C\,. \tag{1}$$

Rotor position sensors change their state at particular angles of rotor position related to the waveforms of the electromotive force (Fig. 2). The rotor position angle can be linearly approximated between these positions assuming constant speed. This idea is used in the ZOA method – Zeroth Order Algorithm [3], the scheme of which is presented in Fig. 3.



(a) (b)

Fig. 2. Waveforms of the electromotive force shape signals (a) and rotor position coding signals (b) as the (electric) position function of rotor

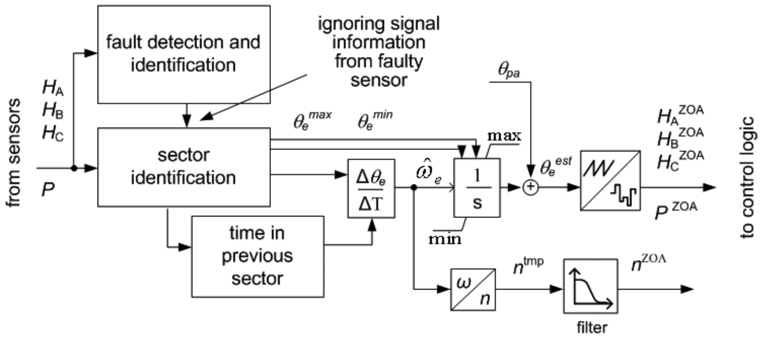


Fig. 3. Determination algorithm of the alternative signals H_k^{ZOA} of the rotor position according to the ZOA method (based on [3])

On the basis of the information about the rotor position sector the minimum $\theta_e^{\min}$ and maximum $\theta_e^{\max}$ value of the position angle (the initial and final value for a given sector) in a given sector is estimated, and the value of the time a rotor spent in the previous sector is used to determine the average speed (2). Next it is integrated (from initial value θ_e^{min}) (3) within the range set by (4). In the last step the estimation of the electrical position angle of a rotor is used to determine the discretised information about the position of alternative signals H_k^{ZOA} $(k \in \{A, B, C\})$, P^{ZOA}, which can be then used in the control system. Due to the fact that angle θ_e^{est} is available, it is possible to correct this value by angle θ_{pa} in a simple way. This option is useful when commutation acceleration/delay is assumed in motor control or if in a given motor position sensors are located in different places than the ones assumed in the control system. The instantaneous signal of rotational speed can be averaged or filtered and used as a feedback signal.

$$\omega_e^{\text{est}} = \frac{\Delta\theta_e}{\Delta T}, \tag{2}$$

$$\theta_e^{\text{est}} = \omega_e^{\text{est}}\Delta t + \theta_e^{\text{min}}, \tag{3}$$

$$\theta_e^{\text{min}} \le \theta_e^{\text{est}} \le \theta_e^{\text{max}}, \tag{4}$$

where ω_e^{est} [rad/s], θ_e^{est} [rad] are the estimated values of the angular (electrical) speed and rotor position, θ_e^{min}, θ_e^{max} [rad] are the minimum and maximum values of the position angle in a given sector, $\Delta\theta_e$ [rad], ΔT [s] are the angular width and time spent in the previous sector of the rotor position and Δt is the time spent by the rotor in the current sector position, respectively. For the purpose of description clarity, angle values in charts are given in (electrical) degrees.

After the occurrence of the fault of a rotor position sensor, there is a change in the number, angular width and limiting angles in particular sectors. Hence the values used in (2) and (4) must be adjusted accordingly, depending on a fault type. To facilitate the analysis in (5)–(7), appropriate multipliers (k^{min}, k^{max}, L) were defined, their values for particular cases were collated in Table 1. After the change of the direction of rotational speed to a negative one, the values of limiting angles θ_e^{min} and θ_e^{max} should be interchanged.

To summarize all above information, Fig. 4. illustrates the information flow in the control system between the state of reading inputs of the rotor position sensors and the using of this

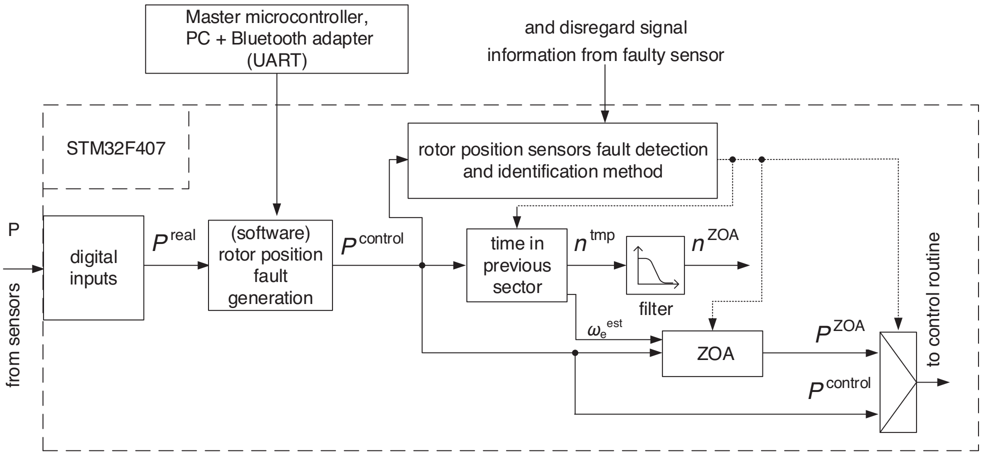


Fig. 4. Information flow – rotor position and rotational speed in the control system

information to control the power transistors. Calculations performed within the ZOA method can also be used to calculate the rotational speed (signal n^{tmp} [rpm]). Because it is characterised by certain instability, related to the accuracy of sensor fitting and the way of measuring time, it has to be averaged/filtered to obtain the signal named n^{ZOA}. Increasing the frequency of calculations positively affects the resolution of time measurement and thus determining the position and speed of the rotor.

Table 1. ZOA method coefficients

<table>
<tr><td rowspan="5">without fault</td><td>$H_AH_BH_C$</td><td>100</td><td>110</td><td>010</td><td>011</td><td>001</td><td>101</td><td colspan="8" rowspan="5"></td></tr>
<tr><td>P</td><td>4</td><td>6</td><td>2</td><td>3</td><td>1</td><td>5</td></tr>
<tr><td>$k^{\min}$</td><td>0</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td></tr>
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<tr><td>$k^{\min}$</td><td colspan="2">0</td><td>2</td><td colspan="2">3</td><td>5</td><td>$k^{\min}$</td><td colspan="2">0</td><td>2</td><td colspan="2">3</td><td>5</td></tr>
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<tr><td rowspan="5">$\boldsymbol{H_C = 0}$</td><td>$H_AH_BH_C$</td><td>100</td><td>110</td><td colspan="2">010</td><td>000</td><td>100</td><td rowspan="5">$\boldsymbol{H_C = 1}$</td><td>$H_AH_BH_C$</td><td>101</td><td>110</td><td colspan="2">011</td><td>001</td><td>101</td></tr>
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</table>

$$\theta_e^{\min}\ [\text{rad}] = k^{\min} \cdot \pi/3, \tag{5}$$

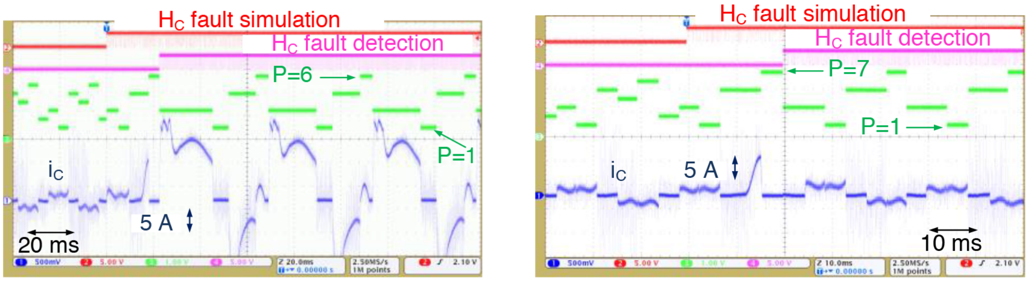
$$\theta_e^{\max}\ [\text{rad}] = k^{\max} \cdot \pi/3, \tag{6}$$

$$\Delta\theta_e\ [\text{rad}] = L \cdot \pi/3. \tag{7}$$

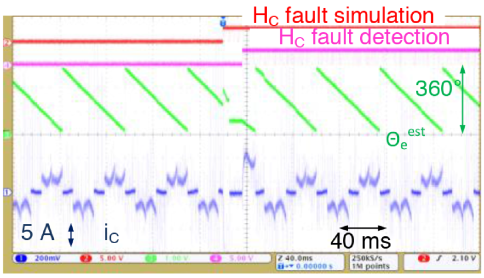
3. Experimental research results

The ZOA method discussed in this paper was firstly implemented in a digital signal processor at a laboratory setup and then it was verified in various work states. The experimental research results from this stage were presented in [12]. Then the prototype of the electric vehicle was prepared (Fig. 1) and in its control program the ZOA method was implemented. The quality of the results depends on the frequency of calculations and determining the time between state transitions of the Hall sensor's signal. In the vehicle control software all the calculations were made for each software cycle, which was equal to the PWM frequency, i.e. 16.8 kHz. So the time basis for calculations is one period of the PWM signal (approx. 59.5 μs). For more accurate calculations for very high speed motors, the method of time calculation between state transitions of Hall sensors can be changed, and utilizing hardware interrupts for state transition identification and timer modules for time measurement.

The first oscillograms (Fig. 5) were recorded at the beginning of the work for validation, if the control software was properly moved from a DSP processor to a microcontroller. The first step (Fig. 5(a)) consisted of checking, whether the fault detection and identification method works properly. It can be noticed, that phase currents have been distorted after fault occurrence, as indicated by the waveform of the current in phase C (marked as i_C). For testing purposes the state of two digital output pins of the microcontroller was indicated to see, whether the position sensor fault was simulated or detected. Other output pins, from a built-in digital to analog converter, indicated the rotor's position (P or θ_e^{est}). Another two figures (Fig. 5(b), Fig. 5(c)) were registered in a system, in which the application of a fault compensation method (the ZOA method) has been used. It can be observed that after a short, temporary period when the faulty element detection and identification process took place, compensating actions were implemented. As a result the operation was continued in such power supply conditions as before the occurrence of the fault. Phase currents again had the shape resembling a rectangle and were symmetrical to each other. Fig. 5(c) presents also the estimated rotor position angle θ_e^{est}, which calculation is based on (2) and (3).



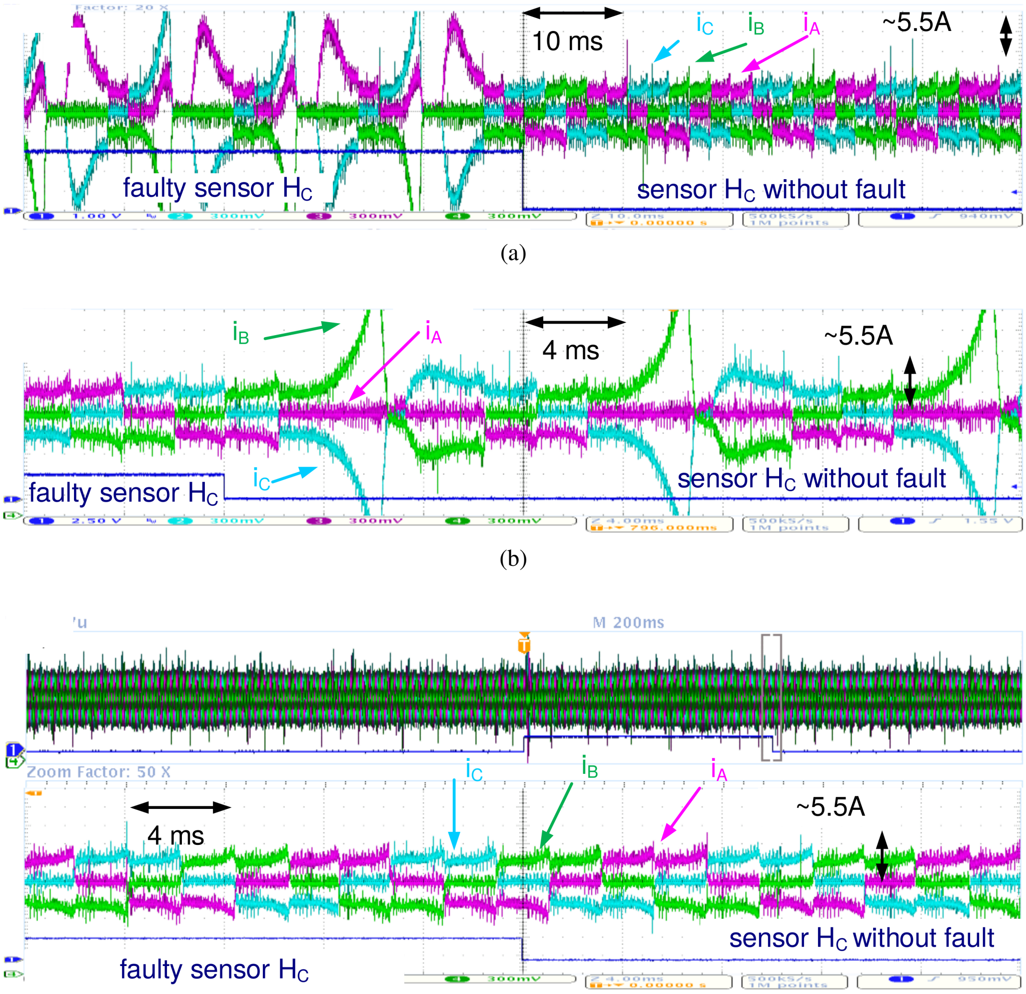
(a) (b)



(c)

Fig. 5. Oscillograms recorded during the validation stage of the detection, identification and compensation methods: case without compensation of H_C sensor fault (a); application of the ZOA method after the detection of the fault (b, c). Signal P is the rotor position sector number seen in the control software (with simulation of one Hall sensor fault), i_C is the C phase current, θ_e^{est} is the estimated rotor position angle

In the previous paper [12] the case, in which the fault state of a Hall effect sensor is temporary (that means the fault disappeared after shorter or longer time), has not been taken into account. For example this may happen due to loose connection of wires or during carrying out researches on the impact of sensor faults. The fault tolerant control systems requires some reconfiguration after detection of the fault. In the case of further operation with the other two healthy sensors – they should reject the signal from faulty sensor. As a result, when the signal from this sensor no longer shows signs of fault, methods such as ZOA will still be able to work properly. Fig. 6 presents examples of waveforms recorded during "disappearing" of the fault. In the first case



(a)

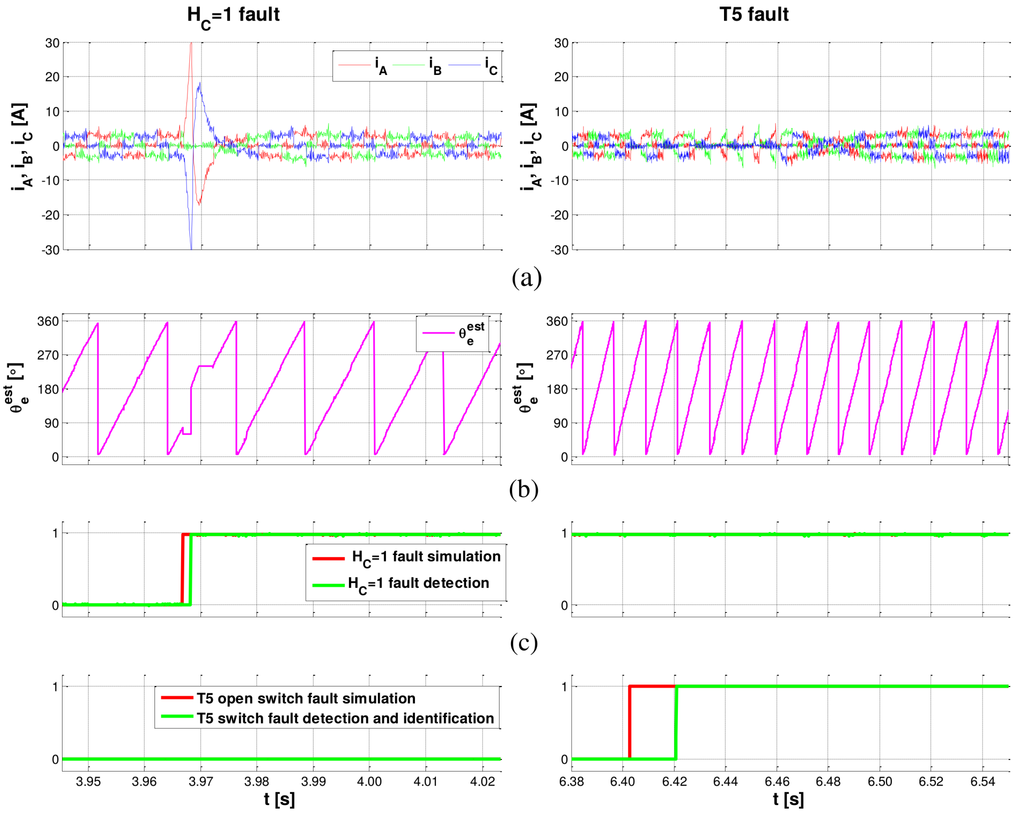
(b)

(c)

Fig. 6. Comparison of phase currents of a loaded motor at the time of self-healing of rotor position sensor fault: case without compensation of fault (a); compensation of fault by ZOA method but without ignoring the information from faulty sensor (b); compensation of fault by ZOA method, signal from faulty sensor after fault ocurrence was ignored in the control circuit (c)

(Fig. 6(a)), a standard control system was used, in which no changes were made in the control method after a fault occurrence, therefore it continues to work properly after disappearance of fault. In the second case (Fig. 6(b)) fault of the Hall sensor was detected, and then the ZOA method was used for compensation. However, the signal from the faulty sensor was not rejected (not ignored), therefore after the automatic “disappearance” of the fault, the input information of the rotor position for the ZOA method is not correct, hence the current pulsation are present waveforms in Fig. 6(b). These pulsations will not occur if the information from the faulty sensor, after its fault, is rejected (Fig. 6(c)). The rejection of the signal was implemented in such a way that after the sensor fault the constant signal value was used instead of the one read from the sensor. If the fault disappears, the input data to the ZOA method will remain correct, and the phase current waveforms also remain correct.

The waveforms from Fig. 5 and Fig. 6 were recorded using the vehicle (from Fig. 1(a)) under “stationary conditions”, i.e. the vehicle was not moving and its wheels were rotating over the ground. However, the waveforms presented in the following figures (Fig. 7–10) will come from



(a)

(b)

(c)

(d)

Fig. 7. Phase currents waveforms (a); estimated rotor position angle (b); information about H_C sensor fault (c) and transistor $T5$ fault (d); during sensor fault and open switch fault simulation while driving vehicle along a straight line

tests of a moving vehicle loaded with passenger. The data were registered using a data acquisition card connected to a laptop powered by batteries. The trajectory of the vehicle movement was referenced as a straight line for comparison of the behavior of a "healthy" drive with the one, in which the faults of the rotor position sensor or transistor in the electronic commutator (open-switch fault) occurred. The detection and identification method of the last type of fault was presented by the author in [4]. An additional redundant branch of the inverter was used in the vehicle for compensation of the open-switch fault. Switching between branches with the faulty transistor to the redundant one was made in the simplest but longest way – two automotive relays were used and the connection of the redundant branch to the motors phase was made after the disconnection of the faulty half-bridge. As can be seen in Fig. 7(a) (on the right), this took about 40 ms, before a single motor phase started to be powered again. This will be change in future work.

The signals of phase currents and the estimated rotor angle have been presented as well as logical signals indicating simulation and detection of faults in the control system. Although the trajectory of the vehicle movement was assumed as a straight line, there are small differences in the amplitudes of the phase currents of both electric motors, which may be related to different values of rolling resistance, e.g. friction between the tire and the ground, acting on individual wheels.

The waveforms from Fig. 7 are part of the longer test drive shown in Fig. 8. The test included simulation of a second type of fault in the same cycle, followed by speed stop, starts and reversals. The example shows that the control system managed these tasks despite the presence of faults.

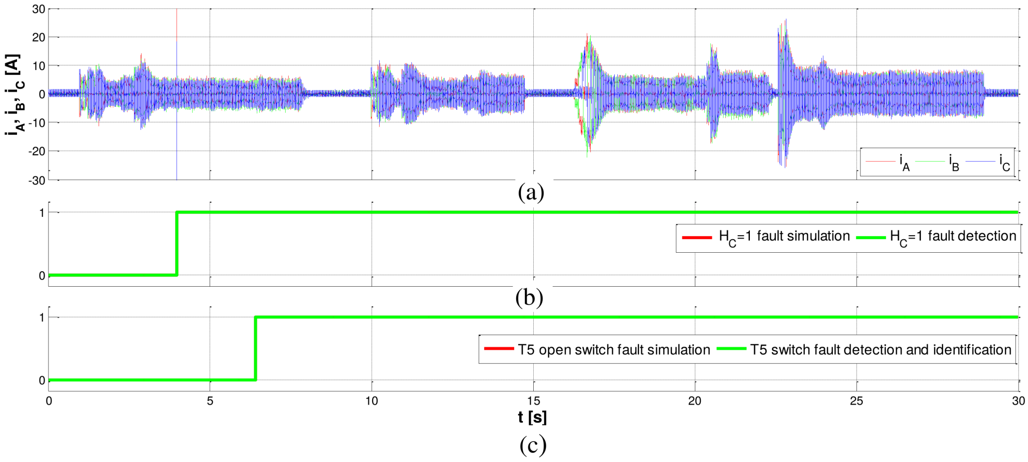


Fig. 8. The whole waveforms of phase currents (a); information about H_C sensor fault (b) and transistor $T5$ fault (c) during rotor position sensor fault and open switch fault simulation and compensation while driving vehicle along a straight line

The next examples concern the comparison of phase currents registered for both drives, in the case of rotor position sensor fault occurrence in one of them (Fig. 9, Fig. 10). After a moment, which was necessary to detect and identify a fault, the ZOA method was used to compensate for the damage. The drive (and the vehicle) continued its work, including start-up and speed reversal.

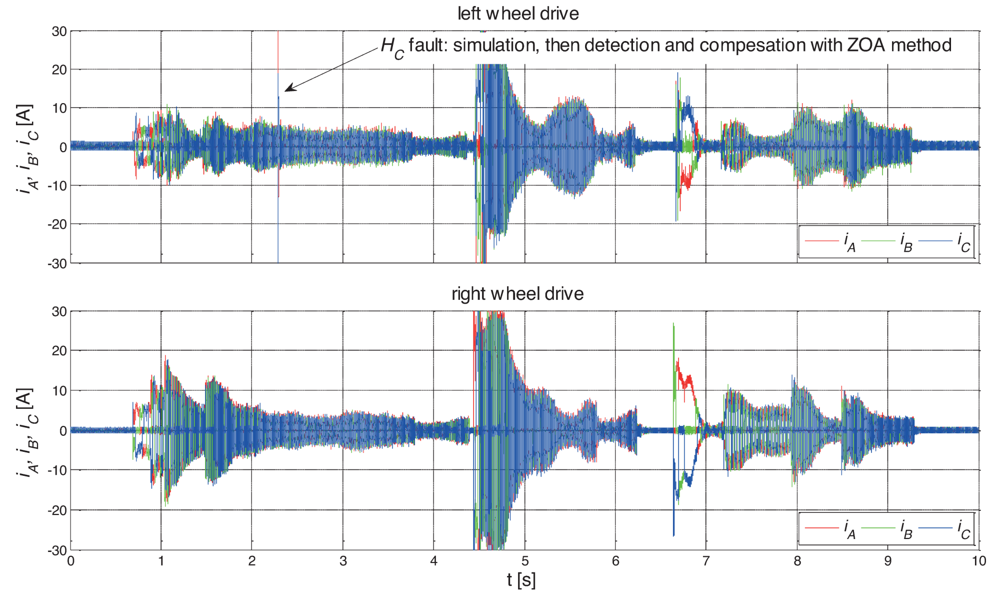


Fig. 9. Phase current waveforms during Hall sensor fault ocurrence in left drive at $t \approx 2.29$ s, while right drive has worked without faults. The fault has been detected and compensated with ZOA method, then the vehicle made speed reversal (at $t \approx 4.5$ s) and start-up (at $t \approx 6.9$ s)

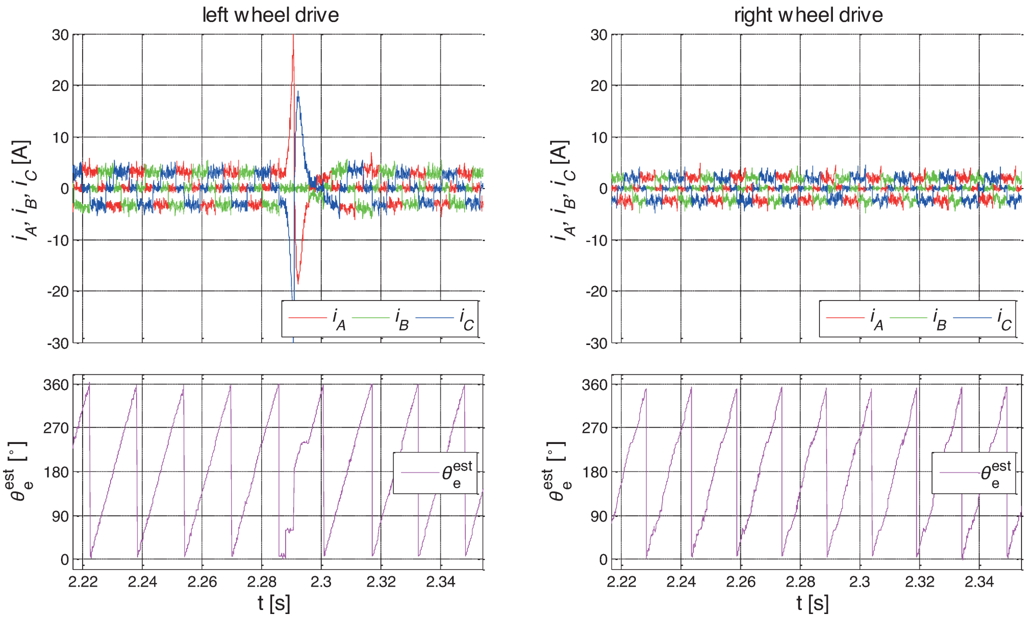


Fig. 10. Zoomed plot of phase current waveforms from Fig. 9 during Hall sensor fault ocurrence in left drive at $t \approx 2.29$ s and additionally estimation of rotor posistion angle (θ_e^{est})

4. Summary

The paper presents the experimental research on the method of the determination of rotor position, necessary in the control system to indicate conducting windings. The selection criterion was implementation simplicity and operation efficiency in a wide range of rotational speeds. This is why classical observers of state variables and sensorless methods were not taken into account. On the basis of the conducted research it was found out that due to the simplicity of calculations (e.g. no trigonometric dependencies) and no additional hardware requirements, the discussed fault compensation method in rotor position sensors can be very useful in the control system of the electrical vehicle drive using a PM BLDC which is currently being developed. The use of the Fault Tolerant Control System (FTCS) ensures continuous drive operation in its natural conditions after the occurrence of a fault and at the same time guarantees safe work, without any surprises, for a vehicle user. The application of the compensation method allows for elimination of work states with deformed phase currents, the disappearing electromagnetic torque and pulse rotational speed (which can have a negative effect on the condition of bearings). It also eliminates additional motor heating and the risk of electronic commutator transistor faults resulting from a too high current occurring after the fault of rotor position sensors which was not compensated. Although the ZOA method is very simple (even there is no necessity to know the parameters of a given motor to implement these methods), the examples have indicated that the method can be quite useful.

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