Virtual prototype for co-simulation of hub-motor dynamics with brushless DC motor and elements of fault-tolerant control

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Abstract. The paper describes the virtual prototype of the hub-motor with a planetary gear, brushless direct current motor (BLDCM) and a fault-tolerant control system for Hall Effect sensors failure. The co-simulation model of the BLDCM control system with integration of the hub-motor mechanical part constructed in MSC Adams software based on PI controllers, pulse width modulation (PWM), and fault-tolerant algorithms for Hall Effect sensors failure is described. Simulation results of the hub-motor virtual prototype with the fault-tolerant control system are shown and discussed.

1. Introduction
Virtual prototyping or digital mock-ups design technology allows reducing development costs and time and increasing product innovation, quality, and flexibility [1]. This is especially important when solving problems of developing and researching new methods to improve reliability and to ensure survivability of expensive technical devices and systems. One of these tasks is to increase the survivability of automatically controlled vehicles (AGV), in which the drive mechanism is the core element determining their performance and, at the same time, prone to failure [2]. The technology of using hub-motors or electric motors mounted in the wheel hub, usually in combination with gearboxes and braking mechanisms, significantly simplifies the transmission design, eliminates the need for a differential, improves weight and size characteristics [3] and implements the ideal concept of driving electric cars and other electric vehicles [4].

Hub-motor failures during operation can occur in case of defects in mechanical components (bearings, shafts, planetary gears, etc. [5]) due to their wear or excessive loads, or in case of a failure of electric motors or elements of their control systems [6].

Inside the hub-motors, it is preferable to use brushless DC motors (BLDCM), which have a number of indisputable advantages compared to collector motors: no collector, compactness, increased efficiency, good positioning accuracy. The control system of the BLDCM typically consists of the following parts: power conversion inverters, a sensor subsystem for determining the rotor position, usually based on Hall sensors, speed, torque or current controllers [7].

The questions of simulation of the BLDCM and their fault-tolerant control systems dynamics are detailed considered in a number of papers, for example [8, 9]. However, in the presented models of the BLDCM control systems, the dynamics of the mechanical part motion is described in mathematical form, which, when considering the complex motion of a hub-motor with gears as part of AGV, requires
laborious processing of the model, especially when detailing nonlinear effects inherent to the mechanisms.

Using technologies of virtual prototyping can significantly simplify the process of setting and dynamic analyses of the non-linear models of hub-motor mechanical parts, the detailed implementation of nonlinearities (backlash, etc.), forming the mass-inertia and load characteristics.

Therefore, to investigate the performance of the tolerant hub-motor BLDCM with gear without carrying out full-scale experiments, it is necessary to have its virtual prototype that can be easily integrated into an AGV model and used for nonlinear dynamics co-simulation in case of occurring mechanical defects and electrical faults. In this paper, we present such virtual prototype and its use to investigate the dynamics of the BLDCM installed in the hub-motor with a fault-tolerant control system for Hall Effect sensors failure.

2. Mechanical model of hub-motor constructed in MSC Adams software

The digital mock-up of the “Green E-Motion” hub-motor is shown in Figure 1. It contains BLDCM with two shafts, bearings, planetary gear, to the outer ring of which a wheel rim is attached and tire that can be connected to the floor by contact forces, defining static and dynamic friction, etc. When simulating the mechanical part, the backlash in the planetary gear, the friction in the bearing and other nonlinearities inherent in the mechanisms are taken into account. The input variable of the model is the torque transmitted to the rotor of the electric motor, the output ones are the angular displacement and angular speed, transmitted to the model of the control system. Mass-inertial characteristics are set according to the catalog data of the elements or determined by the 3D geometry and material properties. Thus, a load torque close to the real applied to the virtual prototype BLDCM rotor.

![Figure 1](image)

Figure 1. A hub-motor with a planetary gear: a – physical mock-up; b – digital mock-up, c – internal structure of the digital mock-up.

3. Mathematical model of BLDCM

BLDCM dynamics with Y-connection of the windings can be described by the following system of equations [10]:

\[
\begin{align*}
  v_a - v_n &= R_a i_a + L_a \frac{d}{dt} i_a + e_a, \\
  v_b - v_n &= R_b i_b + L_b \frac{d}{dt} i_b + e_b, \\
  v_c - v_n &= R_c i_c + L_c \frac{d}{dt} i_c + e_c, \\
  T_e &= k_f \omega_m + J \frac{d\omega_m}{dt} + T_L,
\end{align*}
\]

where symbols \( v \) denote the potentials at the indicated points (figure 2); \( i \) – phase currents; \( e \) – phase back-EMF; \( R \) – rotor windings resistance; \( L \) – rotor windings inductance, \( T_e \) – electric torque; \( T_L \) – load
torque; \( J \) – rotor inertia; \( k_f \) – friction coefficient; \( \omega_n \) – rotor angular velocity.

The back EMF and electrical torque can be written as follows:

\[
e_a = \frac{k_e}{2} \omega_m F(\theta_e), e_b = \frac{k_e}{2} \omega_m F\left(\theta_e - \frac{2\pi}{3}\right), e_c = \frac{k_e}{2} \omega_m F\left(\theta_e - \frac{4\pi}{3}\right),
\]

\[
T_e = \frac{k_i}{2} (F(\theta_e) i_a + F\left(\theta_e - \frac{2\pi}{3}\right) i_b + F\left(\theta_e - \frac{4\pi}{3}\right) i_c).
\]

where \( k_e \) and \( k_i \) – constant of back EMF and torque respectively, \( \theta_e = \theta_m p/2 \) – electric angle, \( \theta_m \) – rotor angular displacement, \( p \) – number of pairs of poles. Function \( F(\theta_e) \) gives trapezoidal shaped back EMF. One period of this function can be written as:

\[
F(\theta_e) = \begin{cases} 
1, & x \in \left[0, \frac{2\pi}{3}\right] \\
1 - \frac{6}{\pi} \left(\theta_e - \frac{2\pi}{3}\right), & x \in \left[\frac{2\pi}{3}, \pi\right] \\
-1, & x \in \left[\pi, \frac{5\pi}{3}\right] \\
-1 + \frac{6}{\pi} \left(\theta_e - \frac{5\pi}{3}\right), & x \in \left[\frac{5\pi}{3}, 2\pi\right]
\end{cases}
\]

4. A co-simulation model of the BLDCM control system as a part of the hub-motor

Figure 3a shows the BLDCM co-simulation model, realized in MATLAB/Simulink software, consisting of a motor model, a switching node, an inverter and a control system with PWM and PI-controller by torque and angular velocity.

The “clockwise”, “inverter” and “BLDC” subsystems represent the BLDCM model without a control system. The “clockwise” block generates values that arrive at the switches of the semiconductor switching node, depending on the position of the rotor, in accordance with using the soft chop (Figure 3b). The BLDC block (Figure 3c) provides communication of electric and mechanical models of the hub-motor virtual prototype in the nonlinear co-simulation mode so that the equation (2) calculated in the MSC.Adams. The “Trapez_calc” subsystem defines equation 4 (Figure 3d). The “Trapez_func” block forms a system of equations 5 (Figure 3e) and the signal denoting the interval of rotation of the rotor using the S-function “delH”, which can also determine sensor faults. To simulate the failure of a specific Hall sensor at a given time, an additional value was added to the input of the S-function “delH” using the “Step” block. This block configures the time after which the sensor will receive a fault using the “Step time” field and its type (ie, the output of the Hall sensor is always “off” or always “on”), which is set in the field “Final value” by the following principle: the value consists of two digits, where the first is the Hall sensor number, the second is its output value. For example, if “Final value” = 21, it means that \( H_i \) = 1, where \( H_i \) – the constant state of the i-th Hall sensor. So the S-function “delH” processes an encoded value of the fault. In order to start the BLDCM and diagnose a “Hall sensor” malfunction,
the algorithms of forced switching of the inverter switches and analyzing all sensors state during one rotation of the rotor are implemented in the S-function “Soft-chop”. The fault-tolerant control system compensates the failed Hall sensor by calculating the period of changing the state of the corresponding inverter switches based on the data of two working sensors.

The mathematical model of the motor electrical part, described by the system of equations (1), is implemented on the elements of the powerlib library (Figure 3f). The input of the inverter unit receives the values of the back EMF, and the control signals from the clockwise unit to the g port of the “Universal Bridge” unit.

The calculation of PI-controllers parameters was carried out according to the method described in [11]. As the result of calculation, torque and speed controller proportional and integration coefficients equal $k_{t_p}=2.5488$, $k_{t_i}=248.2.9$ and $k_{w_p}=0.6975$, $k_{w_i}=0.958$, respectively.

![Figure 3. A co-simulation model of the fault-tolerant control system for BLDCM rotor angular velocity.](image)

5. Co-simulation results and discussion
For numerical calculations, the parameters of the BLDCM Maxon EC 160 W (catalog number is 543673) which are similar to the BLDCM using in the “Green E-Motion” hub-motor were applied.

The co-simulation results of the hub-motor BLDCM dynamics in smooth running, in case of the Hall sensor failure and fault-tolerant control for reference angular velocity signal $\omega_{ref}=10$ rad/s, are shown in Figure 4. As can be seen (Figure 4a, 4b), the amplitude value of the phase current $I_a$ corresponds to
the electrical torque $T_e$ controlled in the inner control loop, determined as $T_e = |I_a| k_t$, where $k_t = 7.12 \times 10^{-2}$ N·m/A – torque constant. According to Figure 4c, PI control of the hub-motor ensures no overshoot and steady state error. Settling time is $t_s = 0.53$ s, rise time is $t_r = 0.3$ s. In the case of the Hall sensor fault ($H_1=0$), the pattern of Hall sensors changes (Figure 4d), which leads to change in the shape of the current and torque graphs (Figure 4a, 4b), as well as to a decrease in the quality indicators of the rotational speed control (Figure 4c) arising an oscillations of the output parameter and a static error. The algorithm of the fault-tolerant control ensures the fulfillment of the control objective with a little deviation.

![Figure 4](image)

**Figure 4.** Co-simulation results of the hub-motor BLDCM dynamics when the first Hall sensor became always “off” since 0.5 s: a – phase current; b – electrical torque; c – angular velocity; d – rotor position (Hall sensors state).

If a Hall sensor fails until the rotor accelerates, the motor will not have enough time to turn to the required angle and stop (Figure 5). Using the algorithm of the forced changing state of the inverter switches together with the fault-tolerant control provides to reach to the system setpoint with a small deteriorating of the dynamics (Figure 5).

![Figure 5](image)

**Figure 5.** BLDCM rotor speed during the Hall sensor fault ($H_1=0$) from the start of the hub-motor.

6. Conclusion
The general co-simulation results of the hub-motor dynamics with BLDCM and fault-tolerant control system are similar to the findings described in [8, 9, 12]. At the same time, the constructed virtual prototype of the hub-motor made it possible to significantly simplify representation of the mechanical part, to take into account the mass-inertial properties of the wheel, to detail non-linear effects (backlash, friction, etc.) in the planetary gear. Also it provided wide opportunities for investigation of modeling of the influence of failures of both electrical and mechanical components on the dynamics of control systems without resorting to physical modeling.

The resulting digital mock-up can be easily integrated to a mobile robot (for example, AGV [13]) chassis, which will allow investigating the effect of failures in the overall operation of the AGV, as well as developing methods of fault-tolerant control for onboard systems.

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