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Operation of aerial inspections vehicles in HVDC environments Part B: Evaluation and mitigation of magnetic field impact

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Abstract. Using robotic systems to conduct remote inspections of offshore wind farm HVDC converter stations has been proposed as a promising solution to reduce the operation and maintenance (O&M) down-time and costs. However, the nature of the electromagnetic field environment inside HVDC valve halls presents a challenge for the operation of traditional off-the-shelf inspection robots. High electrostatic interference to inspection unmanned aerial vehicles (UAV) has been studied in Part A of this paper. In Part B, the impact of the external magnetic field on the operation of an inspection quadcopter’s propulsion motors is assessed. An experimental method is proposed to identify the maximum magnetic field tolerable by off-the-shelf quadcopter motors. The reported method can be used to test commercial off-the-shelf quadcopter motors to identify their suitability for use in HVDC valve halls inspection robots. The paper experimental results show the failure of direct torque control (DTC) algorithm, that is used in quadcopters speed controllers in mitigating the magnetic field impact on motor’s speed and current consumption.

1. Introduction

Monitoring high voltage direct current (HVDC) valve halls, using unmanned aerial vehicles (UAV) is accompanied with high electromagnetic field interference risks. High electrostatic field interference has been studied in Part A of this paper. In Part B, high magnetic field interference risks are identified and investigated in depth. Nominal magnetic field of, twelve-pulse valve in HVDC converter station is reported in [1] to be 9 mT, using thyristor module technology. However, in faulty conditions the magnetic field can exceed this value causing high magnetic field interference. High magnetic field can influence the nominal operation of UAV motor in terms of its speed and current consumption. Also, it can influence the nominal operation of some sensors that rely on the magnetic field for its operation such as magnetometers.

In this paper a rigorous study of DC magnetic field impact on off-shelf UAV motors together with its electronic drive controller unit is presented. In our work, the effect of the magnetic field is monitored through observing two parameters: (1) Current Consumption, and (2) Motor Speed. A typical UAV flight controller adjusts the drone throttle, roll, pitch and yaw through
controlling the speed of each motor with the aid of electronic speed controller (ESC). Brushless DC (BLDC) motors are widely used in commercial UAVs, since they offer better cooling and higher voltages to be achieved. Moreover, BLDC motors replace the mechanical commutation with electronic commutation, which enables the motor armature to be on the stator for more flexible UAV motor design [2].

The control of BLDC motor can be either sensored or sensorless. BLDC motor sensorless control has the advantage of minimum cable connections and hence more reliability, however it requires more complex computations in the control loop. Back electromotive force (EMF) voltage is used in sensorless control for rotor position estimation instead of Hall-effect sensors in sensored methods.

Vector control algorithms like direct torque control (DTC) had been commercially widely used and implemented in different robotic and UAV architectures to control BLDC motors [3–7]. DTC method relies mainly on selecting the proper voltage vector to drive BLDC motor from a look-up table, using the magnitudes of torque and flux errors. This flux and torque error is computed, using DTC state equation that relates the current vector to the back-EMF vector [4]. However, the study of high external magnetic field impact on DTC algorithm performance was not covered in previous literature.

For high magnetic field test, the paper presents the design of a magnetic field test rig, which can produce variable magnetic field densities with maximum magnitude of 0.2 T, which is sufficient to simulate the faulty cases in which the magnetic field density will exceed multiples of nominal magnetic field at 9 mT. The test rig is composed of a C-shaped magnetic core, whose dimensions are calculated based on accurate simulations to generate the required magnetic field inside the air-gap, which simulates the real magnetic field inside HVDC valve hall.

The paper is organized as follows, in Section II, a theoretical background of DTC algorithm is presented, highlighting the main part which can be affected by exposing the motor to high magnetic field. In Section III, test rig simulations and dimension calculations are presented. In Section IV, the experimental results are analyzed and the paper is concluded in Section V.

2. DTC Control Algorithm of BLDC Motor

A BLDC motor is permanent magnet rotor with 3-phase winding pairs symmetrically distributed on the stator. The motor is connected to pulse width modulated (PWM) inverter, which energizes two motor phases at a time with predefined switching frequency according to rotor speed and position [8]. DTC relies on the principle of direct control of the electromagnetic torque through optimum selection of the PWM inverter switching voltages.

The torque and flux error are maintained within specific limits through hysteresis controller. The relation between the voltage and the current of each motor phase is obtained, using the following relation:

\[
\begin{bmatrix}
V_a \\
V_b \\
V_c
\end{bmatrix} =
\begin{bmatrix}
R & 0 & 0 \\
0 & R & 0 \\
0 & 0 & R
\end{bmatrix}
\begin{bmatrix}
i_a \\
i_b \\
i_c
\end{bmatrix}
+ \begin{bmatrix}
L & 0 & 0 \\
0 & L & 0 \\
0 & 0 & L
\end{bmatrix}
\frac{di}{dt}
\begin{bmatrix}
i_a \\
i_b \\
i_c
\end{bmatrix}
+ \begin{bmatrix}
e_a \\
e_b \\
e_c
\end{bmatrix}
\] (1)

where \( V_a, V_b \) and \( V_c \) are the three phases voltages, \( i_a, i_b \) and \( i_c \) are their corresponding phase currents, \( e_a, e_b \) and \( e_c \) are the back-EMF of the three phases, \( R \) and \( L \) are the motor winding resistance and inductance, respectively.

The electromagnetic torque can be obtained from the mechanical torque as:

\[
T_e = T_m + B\omega_m + J\frac{d\omega_m}{dt}
\] (2)

where \( T_e \) and \( T_m \) are the electromagnetic and mechanical torques, respectively. \( B, \omega_m \) and \( J \) are friction coefficient, rotor angular velocity and inertia, respectively. DTC method requires the
transformation from the three phase \((a, b \text{ and } c)\) domain to the two phase \((\alpha \text{ and } \beta)\) domain, using Clarke transformation [8] [9]. The transformation can be represented as:

\[
i_{\alpha,\beta} = [T]i_{a,b,c}, V_{\alpha,\beta} = [T]V_{a,b,c}
\] (3)

where \(T\) represents the transformation matrix from three phase to two phase domain and can be obtained as:

\[
T = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & -\frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}
\] (4)

The stator flux in the \(\alpha - \beta\) domain can be calculated as

\[
\lambda_{s,\alpha,\beta} = \int V_{\alpha,\beta} - Ri_{\alpha,\beta} dt
\] (5)

and the rotor flux can be obtained from the stator one as

\[
\lambda_{r,\alpha,\beta} = \lambda_{s,\alpha,\beta} - Li_{\alpha,\beta}
\] (6)

The torque can be calculated in the \(\alpha - \beta\) domain as

\[
T_e = \frac{3p}{4} \left[ \frac{d\lambda_{r,\alpha}}{d\theta_e} i_{\alpha} + \frac{d\lambda_{r,\beta}}{d\theta_e} i_{\beta} \right]
\] (7)

where \(p\) is the number of motor poles and \(\theta_e\) is the rotor electric angle. Hence, the torque can be expressed in terms of the back-EMF as

\[
T_e = \frac{3p}{4} \left[ \frac{e_{\alpha}}{\omega_e} i_{\alpha} + \frac{e_{\beta}}{\omega_e} i_{\beta} \right]
\] (8)

The error in the flux and the torque is controlled, using a look-up table that generates the voltage vector input to six switches PWM inverter. DTC block diagram is shown in Fig. 1.

As previously mentioned, DTC method is widely used and implemented in UAV ESC to
control UAV BLDC motors [8]. However, equation 8 shows the direct relationship between the electromagnetic torque and the magnitude of the back-EMF, which can be affected in presence of external magnetic field. Hence, a rigorous experimental study is required for the external magnetic field influence on UAV BLDC motor control, using DTC method, which is the main aim of our paper.

Also, the paper studies the external flux impact on motor Kv constant, which represents the ratio between unloaded motor speed to the applied or back-EMF voltage.

3. Magnetic Field Test Rig Design

3.1. Test Rig Simulation

![Figure 2. C-shaped core design and simulation result (a) 2-D FE model geometry (b) Magnetic field density inside the air-gap](image)

Table 1. Simulated magnetic field density inside the air-gap of the magnetic core

<table>
<thead>
<tr>
<th>Coil Current (A)</th>
<th>Air-gap top (mT)</th>
<th>Air-gap middle (mT)</th>
<th>Air-gap bottom (mT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>40</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>10</td>
<td>80</td>
<td>77</td>
<td>80</td>
</tr>
</tbody>
</table>

To expose the motors to a controlled magnetic field, a classical C-shaped core design with appropriate air-gap and wound coil design was used. To determine the optimal geometry/design specification of the core, a detailed parametric geometric finite element (FE) model was developed, using the FLUX2D electromagnetic software package from Cedrat.

The geometry of the core was designed, using parametric FE model of the core. Simulations of the FE model were conducted to emulate the real case scenario of the magnetic field interference. The final developed C-shaped core model including the coil system configuration is shown in Fig. 2a. The simulated magnetic flux density within the air gap of the core, in case of 10 A energized coil, is shown in Fig. 2b. The air-gap magnetic flux density $\phi_{ext}$ values at the two examined current levels are summarized in Table 1.
Figure 3. Motor back-EMF test setup

Figure 4. Motor current and speed test setup
3.2. Test Rig Implementation

The test rig developed in this paper is used to perform two main tasks: 1) Evaluation of BLDC motor velocity constant under the influence of external magnetic field, 2) Testing the variation in BLDC motor nominal operation in presence and absence of external magnetic field.

The main test rig is composed of the C-shaped magnetic core, previously discussed in Subsection 3.1. The magnetic field inside the core is varied, using a controlled DC supply connected to the coils of the core. The core is kept inside an acrylic box for heat insulation, to isolate the heat generated in the coils from the motor under test. The temperature increase does not affect the magnetic flux, however, to test the motor operation within its nominal temperature of operation, it is recommended to isolate the heat induced by the current flow through the coils of the magnetic core.

To test the effect of the external magnetic field on the internal motor flux, the motor velocity constant \( K_v \) should be evaluated in the presence and absence of external magnetic field.

As can be deduced from equation (7) and (8), the ratio between induced back-EMF and the angular velocity \( \omega \) is equal to the rate of change of the internal rotor flux with respect to rotor electric angle \( \alpha \). Hence, monitoring the change in internal motor flux can be achieved through monitoring its \( K_v \) constant.

The setup used to measure the motor \( K_v \) constant is shown in Fig. 3, where a drill is used to rotate the motor inside the air gap of the C-shaped magnetic core. A voltage probe is used to measure the back-EMF voltage induced across the motor different phases wires.

To test UAV BLDC motor in presence of external magnetic field, the test rig is prepared as shown in Fig. 4. The motor is placed in the middle of the C-shaped core air-gap, using an adjustable holder, which can control both the motor height and inclination angle. Simulated magnetic field magnitude inside the air-gap is found in Table 1. The motor speed is controlled, using servo tester connected to an ESC, which supplies the 3-phase current to the motor. The 3-phase current and voltage are measured, using oscilloscope. The real time motor speed is measured, using a tachometer connected to the computer serial port.

4. Magnetic Field Test Setup and Results

4.1. Test Setup

Three different brands of motors are used during the test, which represent different UAV BLDC motor types and technologies that are widely used in the market. The motors are different in terms of dimensions, rpm constant and feedback to corresponding ESC. Air gear and SwellPro motors are sensorless motors, which rely on the back-EMF to determine the rotors position and speed. Also, both motors have rotor as the exterior part of the motor, while the stator is the interior one.

The Turnigy Trackstar 13.5 T motor is sensored BLDC motor, which has three Hall effect sensors connected to determine the rotor position and speed. The Turnigy has the rotor and the stator reversed compared to Air gear and SwellPro motors. The three motors are shown in Figure 5.

![Figure 5. Three motors used in the experiment](image-url)
Fig. 5. A comparison between main characteristics of the three motors is presented in Table 2.

Each motor of the three brands is maintained inside the core air-gap, using the adjustable holder. The current, voltage and speed of each motor are measured in presence and absence of the different magnetic field magnitudes, where different motor speeds are examined, using the servo tester.

4.2. Motor Velocity Constant Test Results

The results of the motor velocity constant test are summarized in Table 3. The speed of the motor in this test has not been much affected by the magnetic field, since the rotor is connected to the drill which is located outside the air-gap and maintains a good air clearance distance that damps the external magnetic field. However, the main reason of changing the Kv constant is the change in the induced back-EMF, that occurs as a result of the change in the internal magnetic flux.

The test results show the change in the internal flux of the motor in the presence of external high magnetic field. This flux change leads to a corresponding change in the back-EMF that affect the torque calculations in equations (7) and (8).

4.3. Motor Magnetic Field Test Results

In Figs. 6, 7 and 8, the motor rms current and speed are plotted versus the duty cycle of the PWM signal, which is output from the servo tester. For the three motors, the increase in the current magnitude is observed for all the values of the duty cycle.

In Fig. 6, Air gear motor shows increase in its speed in the presence of the magnetic field for all the duty cycle values. However, SwellPro and Turnigy motors show different behavior regarding the motor speed. In Fig. 7, SwellPro motor speed increases in presence of magnetic field for duty cycle values above 45%, and decreases for values below 45%.

In Fig. 8, Turnigy motor also shows an increase in its speed in the presence of magnetic field for duty cycle values above 70%, and a speed decrease for duty cycle values below 70%. Although the latter two motor brands show different speed behavior, their corresponding ESCs fail to compensate the magnetic field effect though pushing more current to the motor.

The failure in ESC compensation of the magnetic field effect can be explained, using equations 7 and 8, which estimate the torque based on the magnitude of the motor flux and its corresponding back-EMF, which is affected by the presence of external magnetic field, as shown in the motor Kv constant evaluation test. Hence, the calculations of both the reference torque and the estimated torque are not totally accurate, which leads to wrong input to the voltage

<table>
<thead>
<tr>
<th>Table 2. Comparison between different BLDC motor types</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Rotor position detection method</strong></td>
</tr>
<tr>
<td>-------------------------------------</td>
</tr>
<tr>
<td>Maximum input current</td>
</tr>
<tr>
<td>Nominal voltage</td>
</tr>
<tr>
<td>Dimensions</td>
</tr>
<tr>
<td>KV constant</td>
</tr>
<tr>
<td>Main application</td>
</tr>
</tbody>
</table>
Table 3. Motors velocity constant test results

<table>
<thead>
<tr>
<th>Motor</th>
<th>Motor Speed (rpm)</th>
<th>Peak-to-Peak Voltage (v)</th>
<th>Kv</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air gear motor</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Magnetic field</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>current (T)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>1303</td>
<td>3.38</td>
<td>771</td>
</tr>
<tr>
<td>$77 \times 10^{-3}$</td>
<td>1280</td>
<td>2.81</td>
<td>911</td>
</tr>
<tr>
<td>Swell Pro motor</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Magnetic field</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>current (T)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>1263</td>
<td>4.88</td>
<td>517</td>
</tr>
<tr>
<td>$77 \times 10^{-3}$</td>
<td>1220</td>
<td>3.41</td>
<td>715</td>
</tr>
<tr>
<td>Turnigy Trackstar motor</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Magnetic field</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>current (T)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>1460</td>
<td>1.91</td>
<td>1528</td>
</tr>
<tr>
<td>$77 \times 10^{-3}$</td>
<td>1451</td>
<td>1.5</td>
<td>1934</td>
</tr>
</tbody>
</table>

Figure 6. Air gear motor current and speed versus PWM duty cycle

Figure 7. SwellPro motor current and speed versus PWM duty cycle

5. Conclusion

An inspection UAV for HVDC valve halls is a challenging monitoring solution. The high magnetic field inside the valve hall can affect the nominal operation of the UAV BLDC motors. In this paper, the DTC control algorithm for UAV BLDC motors has been studied and tested under the influence of high DC magnetic field. Although the ESC pushes more current to the motor, it fails to compensate the magnetic field impact. This takes place as a result of inaccurate torque estimation in the presence of external magnetic field. In order to mitigate the effect of the magnetic field, a speed control algorithm is advised to be developed and implemented in the ESC of valve hall inspection UAV instead of the torque control algorithm, which is currently adopted by commercial ESCs. Although only DC field effects are analysed in this study, the developed test system enables assessment of an arbitrary frequency external magnetic field influence on propulsion motor operation.

Future work is planned to study the performance of different motor orientations with respect
to external magnetic field. Also, a mitigation criterion should be developed for external magnetic flux interference through using different control algorithms with the aid of BLDC motor control evaluation boards.

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References