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DESIGN OF UNIVERSAL CONTROL UNIT FOR BRUSHLESS DC MOTORS

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Abstract: *The paper presents the design of both power and control electronics used to develop a universal BLDC (brushless DC) motor control unit intended for an aircraft fuel metering pump. The controller allows employing various methods for sensor and sensor-less control including frequency, trapezoidal, sinusoidal and fielding oriented control. The power subsystem provides three power totem-pole switches as well as a wide range of input and auxiliary circuitry. As needed by the target aircraft industry standards, conclusions of a thorough FMECA analysis of the resulting device are given.*

Keywords: ***BLDC motor, control unit, model based design***

1. Introduction

The Brushless Direct Current (BLDC) motors have recently gained substantial popularity among applications that require increased mechanical reliability, operation in explosive or otherwise harsh environments and accept slightly higher demands on the control unit. It has been proven that BLDC motors are suitable for use in critical control applications in aerospace due to their architecture, performance and characteristics. One of such applications is a fuel metering pump drive that is being developed as a part of the CESAR (Cost Effective Small Aircraft) EU project.

The operation of any aerospace actuator based on a BLDC motor (e.g. the fuel metering pump) is safety-critical and its safe operation requires a reliable control algorithm that ensures safe start-up and running of the BLDC motor in the whole operation range. Several applicable control algorithms and methods which have been evaluated within the CESAR project are described hereinafter as well as the controller itself that host these algorithms.

2. BLDC motor control theory

Brushless DC motor (BLDC, also known as electronically commutated motor) is from the construction point of view very similar to the synchronous motor with permanent magnets in the rotor. The main difference is usually different shape of the developed EMF waveform – trapezoidal for BLDC (simple block commutation optimization) and sinusoidal for synchronous motors (complex sinusoidal control).

From the modeling perspective, the trapezoidally wound BLDC motor can be perceived as a DC motor whose mechanical commutator is replaced by electronic means, i.e. by sequential switching of the windings to the power. This similarity implies that the quantities current-torque and voltage-speed are linearly dependent.

2.1. Frequency control

The basic control principle of the BLDC motors is frequency control. In its simplest form, called trapezoidal control or six-step commutation, it provides a winding power switching sequence as a replacement of the mechanical commutating device. As Fig. 1a depicts, the commutation law defines six succeeding states with only two windings powered simultaneously (the third one is left floating).

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The biggest strength of this method is its simplicity; on the other side, the moment control at lower speeds is rather worse which leads to moment and speed pulsations.

The other technique – sinusoidal control – overcomes this ripple by harmonic driving of all three windings at the same time. Smoothly rotating current space vector has a constant magnitude and is always in the quadrature direction to the rotor, as shown in Fig. 1b. However, the complexity of this control method is much higher compared to the trapezoidal commutation. A precise position of the rotor has to be known; moreover, the sinusoidal commutation is prone to be suboptimal in the area of higher angular speeds. The reason is that the winding current magnitude controllers are limited in their bandwidth and are not able to precisely follow fast harmonic signals.

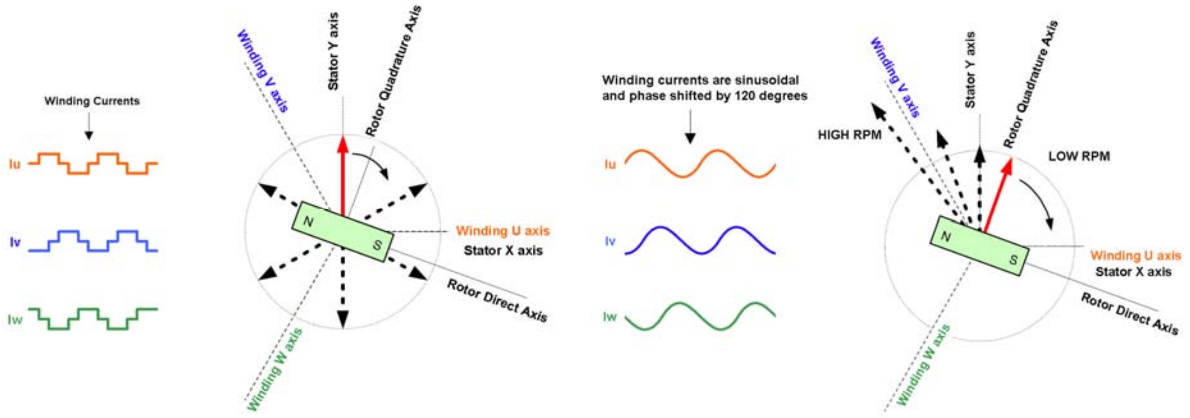


Fig. 1: Commutation law of a) trapezoidal control b) sinusoidal control (Microchip, 2011)

2.2. Field oriented control (FOC)

FOC overcomes the problem mentioned in the previous paragraph by direct control of the current space vector in the rotor coordinates. This vector should have a fixed size and its direction should be perpendicular to the rotor (quadrature axis). The current control is then provided also in the rotor coordinates which means that the control problem transforms from exact tracking of a sinusoidal signal to much simpler regulation of steady quantities. This ensures that the quality of current control is independent on rotor angular velocity. The technique that allows such a control method is the Park's forward and inverse transformation between the three-phase stator coordinate system and the rotor d-q coordinate system. Because the frequency of these transformations calculation has to be the same as the needed working frequency of the current control loop, the FOC is quite heavy on computational power of the host system.

2.3. Sensor and sensor-less control

Each control principle has different demands on sensory inputs needed for its successful operation. The simplest case is the block commutation that only needs to know three angular positions where the commutation should occur; this is usually accomplished using Hall or optical sensors. Basically, there are two types of sensor-less control techniques (Leonhard, 2001). The first type is position sensing using back EMF of the motor, and the second one is computational position estimation that uses motor parameters, terminal voltages and currents.

In the case of the sinusoidal-based control methods high-resolution measurements of rotor position are required. Hall/optical sensors produce only discrete information about rotor angular position and do not fulfill the demands; a quadrature encoder or a resolver seems to fit well.

3. Control system architecture

The control system can be divided into two main parts – the control unit itself and a software tool for diagnostic/control purposes. The control unit is further comprised of its hardware platform (providing power electronics, sensory, computations means and auxiliary circuits) and firmware equipment (implementing described control algorithms).

3.1. Hardware subsystem

The hardware development has been conducted in order to comply with aerospace quality standards, including RTCA/DO-254 – “Design Assurance Guidance for Airborne Electronic Hardware” (FAA Advisory Circulars, 2005) and RTCA/DO-160F – “Environmental Conditions and Test Procedures for Airborne Equipment” (RTCA, Inc., 2007).

Three milestone hardware versions (and several more development versions) have been developed within the CESAR project. Each new version of the control and power electronics meant progress and new possibilities in the control methods, such as sensor-less or FOC methods. The newest, 3rd, generation is shown in Fig. 2 and consists of a power electronic board to which the control board is connected using a 50-pin connector.

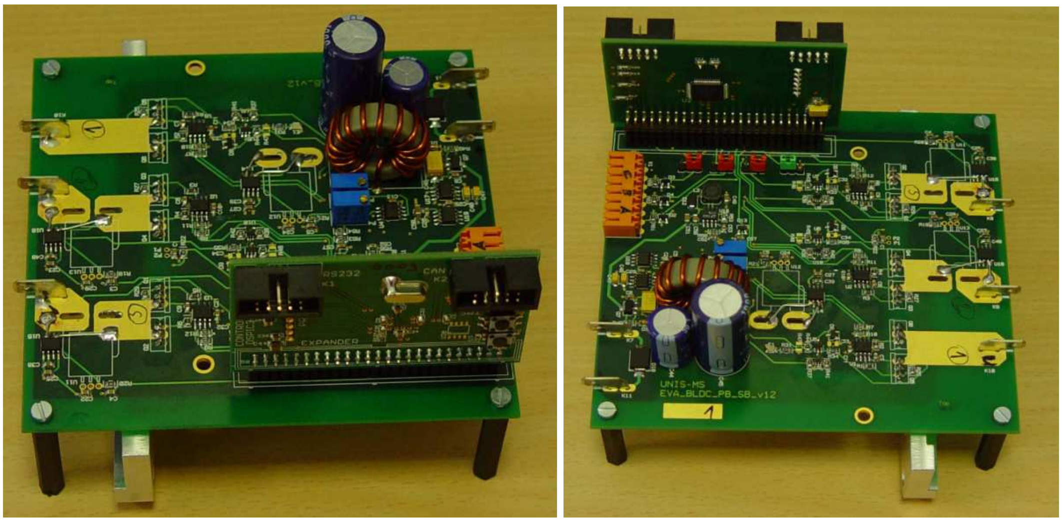


Fig. 2: The 3rd generation hardware

The control board features the Microchip dsPIC30F6015 16-bit DSP that disposes of UART and CAN bus communication lines usable for communication with superior systems. This DSP fully supports motor control applications and has 4 independent PWM channels – 3 for the three-phase power unit and 1 for the electrical brake and PFC of the main DC bus.

The power electronics are composed of three power MOSFET totem-pole switches with appropriate drivers, fast over-current and over-voltage protection circuits and 3 Hall-effect current sensors. Both current shapes – trapezoidal or sinusoidal – are feasible. The analog part of the board allows measuring of back EMF voltages needed for sensor-less control also during the start-up phase, when the angular speed is low.

An extra MOSFET with driver is added onto the main DC bus on this board. If necessary it allows active breaking of connected electrical drive. Performance of this electrical brake depends on the amount of returning energy and recuperation possibilities of main DC power supply.

3.1.1 Firmware

The firmware acts in the following three main roles:

- motor control itself – robust operation of the BLDC motor in all regimes
- safety provision – proper reaction to failure events/states
- communication with master/diagnostic systems – parameter setup, logging etc.

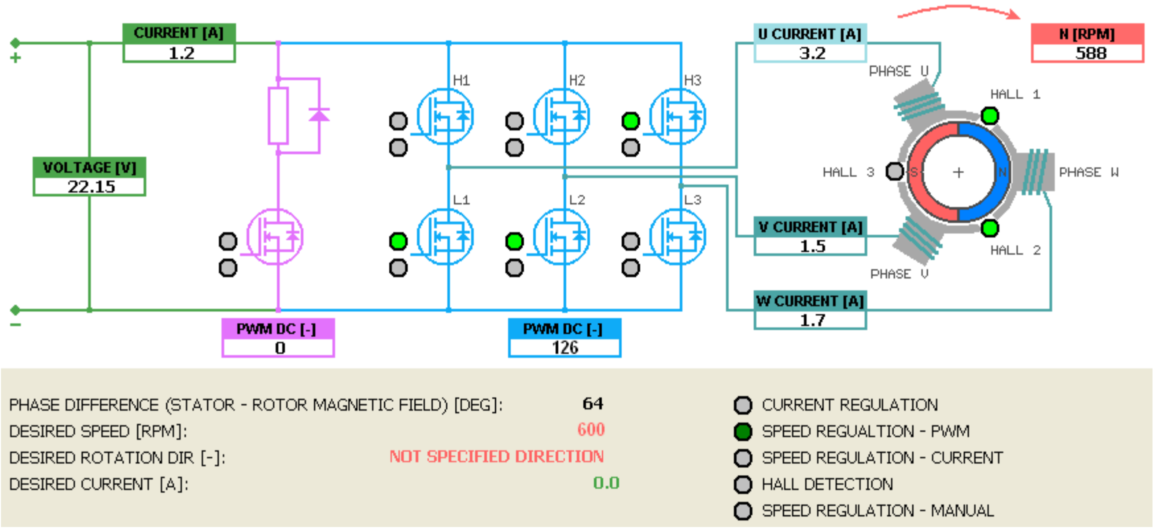
The control principles described in the theoretical section of the paper have been algorithmized and implemented as a part of the control system’s firmware. A MATLAB/Simulink blockset capable of generating C code for the chosen DSP family is available – it can be advantageously utilized for fast functional evaluation of the control algorithms developed using simulations. A benchmarking study of this approach is provided in (Lambersky & Vejlupek, 2011). However, use of the generated code in the final product would not be suitable because of significant demands on code efficiency and reliability originating from the aerospace application area (RTCA, Inc., 1992).

The architecture of the used dsPIC30F6015 DSP is fully optimized for the use of C as programming language. The Microchip-supplied C compiler can also be used in conjunction with the MATLAB/Simulink environment during the Hardware-in-the-Loop development phase.

3.2. Software control tool

Developed control software Graphical User Interface (GUI) is shown in Fig. 3. It depicts a simplified electrical schematic of three MOSFET half-bridge switches and a three-phase BLDC motor. The software communicates via a serial RS-232 line or a CAN bus with the control electronics and displays the main values from the power electronics.

This SW tool works with the presented 3rd version of the control hardware. Operation with the 2nd generation has minor limitations due to its less complex design. The designer can monitor immediate conditions in the circuit; all monitored data can be stored for further analysis.



CURRENT [A] 1.2

VOLTAGE [V] 22.15

U CURRENT [A] 3.2

N [RPM] 588

V CURRENT [A] 1.5

W CURRENT [A] 1.7

PWM DC [-] 0

PWM DC [-] 126

PHASE DIFFERENCE (STATOR - ROTOR MAGNETIC FIELD) [DEG]: 64
DESIRED SPEED [RPM]: 600
DESIRED ROTATION DIR [-]: NOT SPECIFIED DIRECTION
DESIRED CURRENT [A]: 0.0

○ CURRENT REGULATION
● SPEED REGUALTION - PWM
○ SPEED REGULATION - CURRENT
○ HALL DETECTION
○ SPEED REGULATION - MANUAL

Fig. 3: GUI of the control software tool

4. Control algorithm test results

To evaluate the performance of the control system and the designed electronics, two types of the evaluation test were used. Firstly, the start sequence of the fuel pump was performed. The start sequence of the fuel pump, shown in Fig. 4 left, was verified for a step change request from 50 percent of the fuel flow. This means that the starting flow level was 43 l/h (3250 rpm of the BLDC motor) at 2 MPa of back pressure. The required flow after step change should be 92 l/h (7300 rpm of the BLDC motor) at 3.9 MPa of back pressure. The start time of 174 ms was achieved which is acceptable.

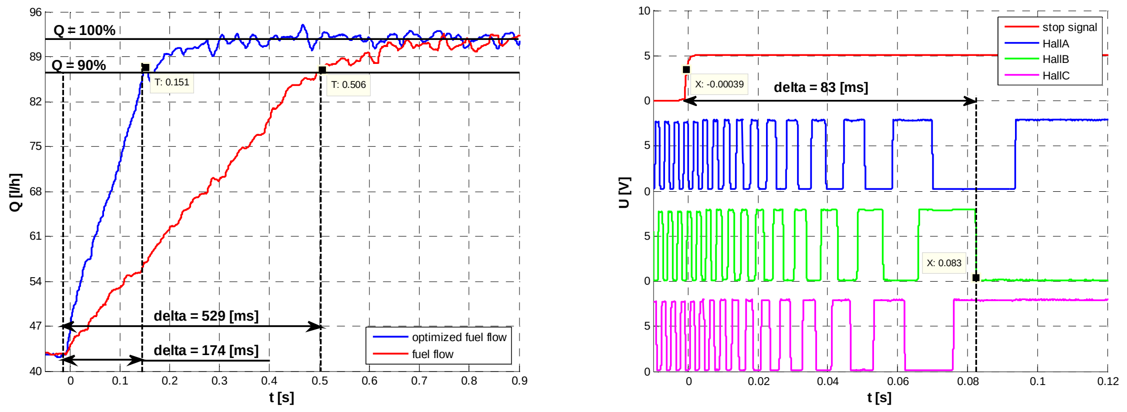


Fig. 4: Start and stop sequence with optimized controller

The next important feature of the fuel pump is the stop time performance. The stop time characteristic was much more difficult to measure. The directly connected speed or flow sensor to the fuel pump influences the stop time characteristic. The only way was to measure the speed from the motor’s internal Hall sensors.

Stop time characteristic is shown in Fig. 4 right. The fuel pump should stop in this case from the nominal fuel flow of 92 l/h (7300 rpm of the BLDC motor) at 3.9 MPa of back pressure. The stop time value of 83 ms was achieved which is acceptable.

5. Failure mode analysis – FMECA

Failure Mode, Effects, and Criticality Analysis is a mandatory part of the development of any electrical application in the aerospace industry. FMECA is also a part of the certification process and there is no possibility to operate any device without the approval of relevant authorities. A preliminary FMECA study of the 3rd generation of electronics was carried out within the CESAR project. The main aim is to find the most critical components in the electrical design and provide a feedback to innovate or supersede critical components. Next to the FMECA analysis, a set of DO-178B, DO-160 (Environmental Conditions and Test Procedures for Airborne Equipment), MIL-STD-810 and other standards have to be followed during the whole development cycle.

5.1. Reliability and safety requirements

The technical life of any actuator and especially a fuel pump should be at least 20 000 hours or 20 years (the earlier applies). In aerospace the probability of failure in a flight hour is usually defined as follows:

- Failure S1 – “Unsolicited FMP running on maximal speed” **10^{-6}**
- Failure S2 – “Lost of regulation” **10^{-5}**
- Failure S3 – “False indication of the FMP failure” **10^{-7}**
- Failure S4 – “Impossibility to stop the FMP” **10^{-6}**

The failure analysis should be evaluated with reference to the outside environmental conditions in one year of operation.

5.2. FMECA conclusions

During the preliminary FMECA evaluation about 859 possible failure states on about 386 failure positions have been analyzed. The most significant failures have been located along a short-circuit path through the semiconductor switching components of the device. Its risk factor RN is higher than 600.

Reliability and safety analysis has found 9 possible failures of the electronic control unit, which can be critical. The most critical devices are semiconductor diodes. The probability of their failure is possible to decrease by usage the special types with higher reliability (devices with the M category dedicated for special purposes).

The overloaded components are usually source of failures and decrease the whole failure probability. According to the FMECA calculations it is not recommended to overload any active or passive components more then 50 % of their maximal values to keep high reliability.

In the conclusion of the FMECA document there is usually a summary of the components that built the whole reliability number. The main rule is not to use complicated integration circuits (such as ASIC circuits), under-designed power semiconductors (diodes, MOSFETs), under-designed electrolytic capacitors and to use as little mechanical connections, connectors, relays etc. as possible (especially no-name low cost devices).

The following Tab. 1 captures the FMECA preliminary results in numbers. F(t) means the probability of failure in one flight hour.

Resulting value	F(t)	Requirement
Failure S1	$1{,}250 \cdot 10^{-8}$	$1 \cdot 10^{-6}$
Failure S2	$1{,}565 \cdot 10^{-6}$	$1 \cdot 10^{-5}$
Failure S3	$1{,}500 \cdot 10^{-8}$	$1 \cdot 10^{-7}$
Failure S4	$3{,}138 \cdot 10^{-8}$	$1 \cdot 10^{-6}$

Tab. 1: The failure probability of FMP system control unit

6. Conclusion

Three evaluation versions of the BLDC motor control hardware have been developed within the CESAR project. With all three generations of electronics we have been able to verify the sensor and sensor-less control algorithms described hereinabove. The optimal control method for the fuel metering pump actuator system has been found: a combination of the sinusoidal frequency start-up phase with operational trapezoidal sensor mode control seems to best fit the needs. The requirements for a fluid metering pump control system have been fulfilled and requested dynamic behavior has been achieved.

In addition it has also been possible to apply and evaluate modern trends in the aerospace industry development. Using appropriate software environment we have been able to prepare a mathematical model of the system and determine suitable settings of the controller during simulation and modeling. This approach, called Model Based Design, is rapidly gaining popularity and its principles have been applied and tested within the CESAR project.

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