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FUTURE TRENDS IN AEROSPACE ACTUATING DEVICES

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Summary: *Development of aviation systems is leading to replacement of traditional centralized hydraulic system by EHA/EMA actuators, which could provide power delivery on demand, and thus remarkably reduce the power consumption of the aircraft. The fundamental principles of EHA/EMA actuators are given and their implementation into distributed control system is proposed. An essential part of any actuator is a BLDC motor, which considerably influences reliability and performance of the actuator. Thus many efforts during the development have been spent on electronics and control algorithms design and verification. EHA/EMA actuator basic, the architecture of a smart distributes actuation control system and modeling of the BLDC motor that drives the actuator are described in this paper.*

1. Introduction

Towards the implementation of Power Optimized Aircraft (POA) by use of Fly-by-Wire (FBW) and Powered-by-Wire (PBW) technologies, Electro-hydraulic (EHA) and Electro-mechanical (EMA) actuators are the most promising technology these days. Nowadays actuators on aircraft are powered from a centralized hydraulic system, which delivers constant pressure for all hydraulic circuits onboard the aircraft. Recent trend is to replace these traditional hydraulic systems by ones with ability to local power delivery on demand. This would lead to considerable reduction of power consumption while keeping the traditional and proven mechanical design principles.

Traditional hydraulic systems onboard the aircraft are powered with constant pressure and the actuator is controlled by orifices. In case of using EHA actuators a local hydraulic circuit is not powered with constant pressure, but with variable pressure that depends on an external load. This variable pressure is then linear controlled by a brushless DC (BLDC) motor with a hydraulic pump, which delivers pressure for the local hydraulic circuit on demand. In case of EMA actuators, the energy is transferred from electrical to mechanical directly by the BLDC motor.

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In comparison to the traditional systems, using electrical energy for supplying the actuators brings more flexibility and ability to reconfiguration upon request and easy maintenance. On the other hand, this technology has a bottleneck in demonstrating reliability in a certification process therefore these systems are usually used in a redundant configuration.

A fundamental element that drives the EHA/EMA actuator is the BLDC motor. In critical applications it is necessary to ensure correct start-up of the motor, therefore the electronics and control algorithm must be safe and robust. An essential part of the development cycle is computer modeling and simulation, which considerably accelerates development and could reveal crucial parts of the designed system, and thus avoid future failures.

2. EHA/EMA actuators

Electro-hydraulic actuators (EHA) are devices that convert electrical energy into mechanical through the hydraulic loop. The concept of EHAs is similar to the traditional hydraulic systems, except that power is delivered into the local hydraulic loop by the BLDC motor with an integrated hydraulic pump. Typically, the EHA actuator consists of the BLDC motor, hydraulic pump, accumulator, filters and block valves. A typical scheme of the EHA actuator is shown in Figure 1.

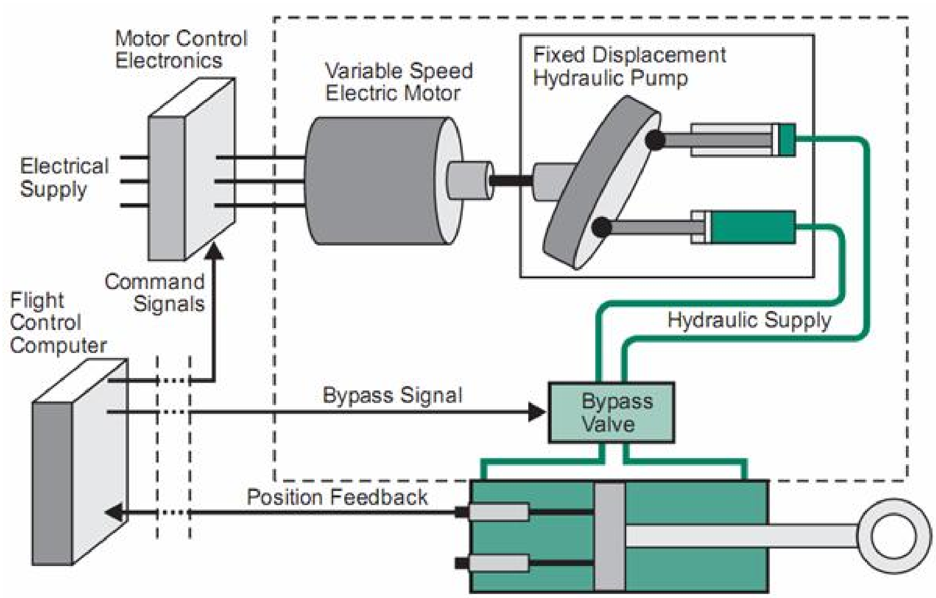

Fig. 1: Typical scheme of an EHA actuator (Botten et al., 2000).

By contrast, electro-mechanical actuators (EMA) are devices that convert electrical energy directly into mechanical by means of some mechanical transmission (e.g. a gear box, ball screw, lever kinematics). The main disadvantage of EMA actuators is possibility of jamming, damping, and overall lower reliability, which makes their use for primary control surfaces impossible. A typical scheme of the EMA actuator with a ball screw is shown in Figure 2.

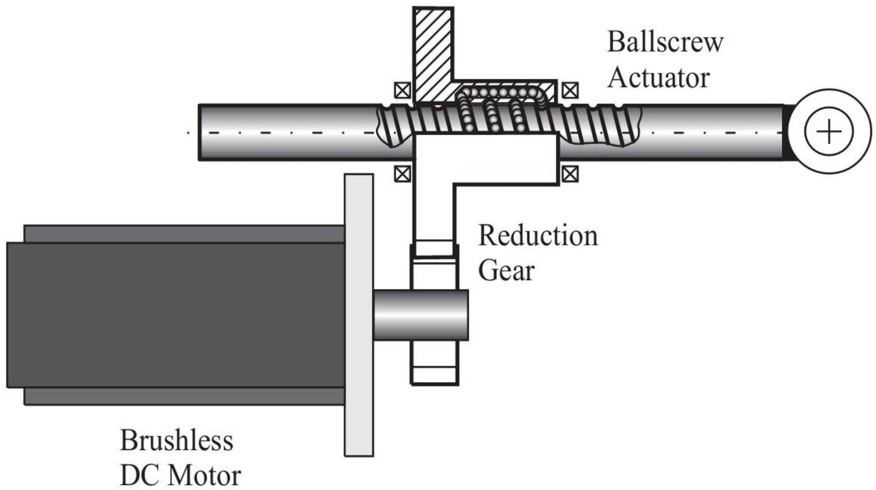

Fig. 2: Typical scheme of an EMA actuator (Cochoy et al., 2007).

Besides flexibility, the use of electrical components in actuators brings also some aspects that considerably influence potential application on control surfaces of the aircraft. These aspects stated below.

Safety: Prior being accepted by certification authority, any complex device must be analyzed, tested and its performance, fault tolerance, and electromagnetic compatibility must be proven. In EHA/EMA actuators, the BLDC motor and electronics are the most critical parts therefore redundant features must be introduced. BLDC motor can be for example configured in redundant mode with two independent rotors and a CPU guardian. On the other hand, this configuration increases weight of the motor and complicates the control algorithm.

Power distribution: Energy supply through power distribution by wires brings flexibility and simplicity in cable routing, segregation of individual power circuits, and ability to easy reconfiguration. Individual power circuits could be also monitored and protected from over-current, which prevent damage of connected devices.

Weight: Elimination of hydraulic leads to overall weight reduction and substantial space savings. Reduction of weight decreases fuel consumption and operational costs of the aircraft.

Maintenance: Maintaining of several simple units is much easier and reliable than maintaining the whole hydraulic loop onboard the aircraft. Reduction of hydraulic components and their replacement by electrical ones increases Mean Time Before Failure (MTBF) and thus overall aircraft safety and reliability.

Replacement: The actuator could be easily modified and adjusted to any architecture used on the aircraft - either the electronics, output power, or communication data bus and protocol. Using unified interface, the actuator could be also replaced with one from a different vendor, while functionality and service provided remain the same.

3. Smart actuation systems

Smart actuation system concept arises from the idea of several independent actuators deployment over the whole aircraft, which cooperate together via a standard communication interface and create a sophisticated distributed control system. A typical aircraft use many actuators for controlling trims, flaps, landing gear, doors etc. These actuators are mostly remote and far distant from an Electronic Control Unit (ECU) that controls their operation. Architecture of smart actuation distributed control system is depicted in Figure 3.

Many technologies have been developed throughout the years, from proprietary solutions to wide-open data buses and protocols, which found their application in the industrial, automotive and aerospace industry. Of the many commercial standards the CAN, TTP, FlexRay and AFDX should be mentioned.

Fig. 3: Distributed control systems (Mital & Jakovljevic, 2007).

Typically, as mentioned above, actuators are controlled by the ECU that sends commands and receives information about current states of the actuator. Beside the control commands and information of actuator's current state, additional information could be sent over the network. This information serves for continuous data storing and health monitoring, which is an essential part of every control system.

Health monitoring provides ability of failure detection and prevention of failures before they come up and cause a critical event. Data stored during the health monitoring could also serve for a further analysis. The data analysis is a basis for on-condition maintenance that significantly reduces the maintenance costs.

Use of a unified communication data bus, protocol and interface allows an easy reconfiguration, replacement and reusability of the actuators. Implementation of smart actuation systems in the aerospace industry brings new opportunities to increase overall system safety and reliability, simplification of assembling procedures and general maintenance.

4. EHA/EMA control system design

The control system of the EHA/EMA actuator consists of three parts that could be interchangeable according to customer needs. These basic modules are Control and Communication Unit, Power Electronics Unit, I/O Unit. The control system architecture is shown if Figure 4.

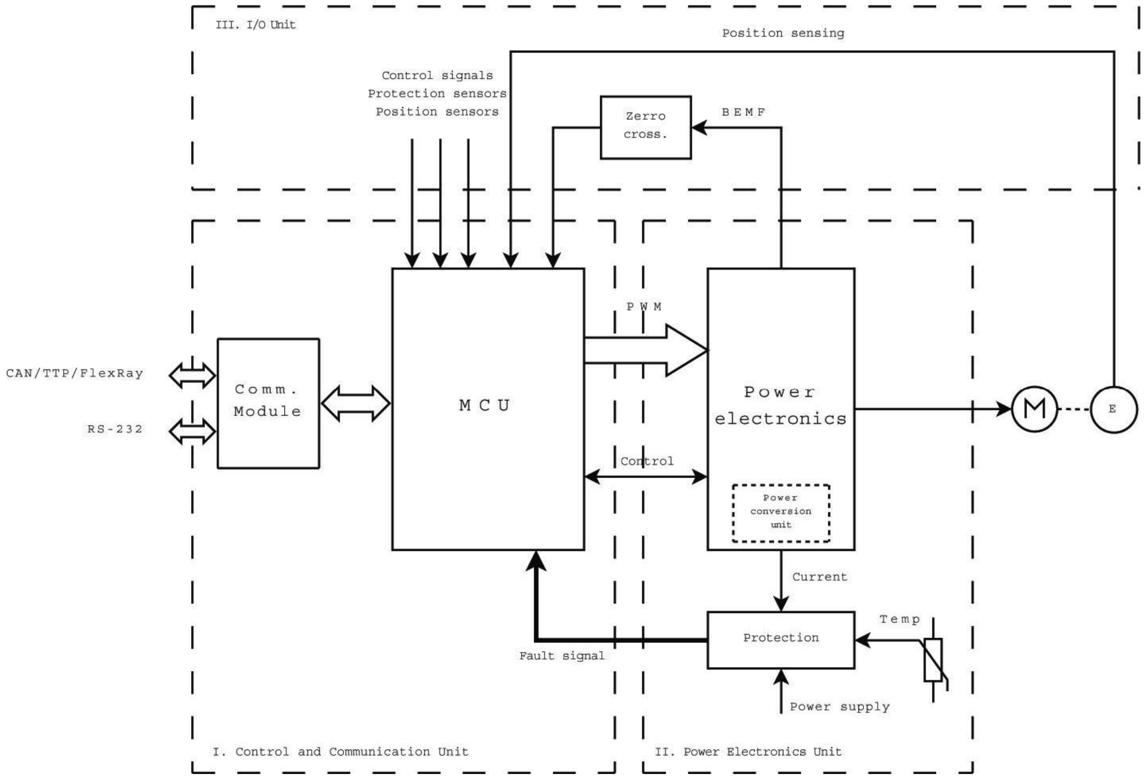

Fig. 4: Architecture of the electronic control system for EHA/EMA actuators.

4.1. Control and Communication Unit

The control computer is mounted on the Control and Communication Unit (CCU). The CCU is replaceable according to application performance requirements and architecture of the control system. The core of CCU is created by a multipurpose microcontroller (MCU).

The CCU has a unified interface for all the analog and discrete signals that are used for control and communication with other control system modules. Using a unified interface enables replacement of the CCU in case of system enhancement or maintenance.

4.2. Communication module

The electronic control system of the EHA/EMA actuator provides selected information of its internal state, measured values, and the actuator's position to the higher-level control system via an internal communication network.

The higher-level control system can be a Flight Control Computer (FCC) or a multifunction avionic display placed in the pilot's cockpit.

From the point of view of cost-effectiveness, the most suitable communication data bus is a serial link by means of a standard data bus that has been proven in the industrial or automotive areas. The data buses with acceptable characteristics for this project have evolved from the original Controller Area Network (CAN) serial communication data bus developed by Bosch GmbH.

The candidates for EHA/EMA actuator communication data bus are:

- CAN
- TTP
- FlexRay

After substantial analysis of these three data buses the CAN has been chosen.

4.2.1. CAN with CANaerospace protocol

Controller Area Network (CAN) is a broadcast, differential serial bus standard, originally developed in the 1980s by Robert Bosch GmbH, for connecting electronic control units (ECUs). CAN was specifically designed to be robust in electromagnetically noisy environments. It can be even more robust against noise if twisted pair wire is used. Although initially created for automotive purposes (as a vehicle bus), nowadays it is used in many embedded control applications (e.g., industrial, aerospace) that may be subject to noise.

CANaerospace is an extremely lightweight protocol/data format definition, which was designed for the highly reliable communication of microcomputer-based systems in airborne applications via CAN. The purpose of this definition is to create a standard for applications requiring efficient data flow monitoring and easy time-frame synchronization within redundant systems. The definition is kept widely open to allow implementation of user-defined message types and protocols.

The data format definition specifies 6 basic message types, which are used for different network services. Each message type has an associated CAN-ID range defining the message priority. The identifier assignment within the specified ranges is at the user's discretion.

4.3. Power Electronics Unit

Power Electronics Unit consists of full H-bridge that is created of six power-switching transistors. BLDC motion is controlled by power switching transistors that switch power supply to the particular coils of the BLDC motor.

An integral part of the Power Electronics Unit is the Protection module that measures temperature, current and voltage on the BLDC motor. In case of any parameter exceeds a limit value the protection module generates a fault signal that enters into the MCU. Detection of the fault signal causes disconnecting of load from the power supply source.

The EHA/EMA actuator is supplied from the aircraft power supply net. Primary supply voltage is supposed to be 28 V DC. Since control electronics operates on lower voltages than 28 V DC, the voltage must be converted to 3.3 V ÷ 5 V (depending on control an electronic design). Linear voltage regulator or a step-down converter could obtain this lower voltage.

4.4. I/O Unit

4.4.1. BLDC motor signals/sensors

Depending on actual configuration, the electronic control system could operate either in sensor or sensor-less mode.

In sensor mode signals from Hall sensors are used as feedback. Its producer usually mounts these sensors inside the BLDC motor. These signals are triggered and used as inputs into the control MCU.

Sensor-less control mode operates on principle of sensing induced voltage caused by Back Electro Motive Force (BEMF) on one of three BLDC motor phases. Feedback is extracted by the means of BEMF and zero-cross detection.

4.4.2. Protection signals/sensors

Monitoring selected parameters and restricting the actuator's fault operation ensure functionality and safe operation of the actuator. If one or more of the signals exceed its limit value, the fault is detected and appropriate action is taken.

4.4.3. Position signals/sensors

The electronic control system for the EHA/EMA is ready for synchronized operation of two actuators. Position of both rams and flap deflection is measured and monitored in real-time by microprocessor system.

In case of detection of difference in the ram position, the malfunctioning actuator must be switched to the state that allows free motion of actuator's ram. In case of emergency, mechanical design allows controlling of the flap deflection using only one of the actuators without functional interruption.

5. BLDC motor architecture

The brushless DC motor (BLDC (Compter, 2007) is a synchronous electric motor that from a modeling perspective looks exactly like a DC motor, having a linear relationship between current and torque, voltage and rpm. It is an electronically controlled commutation system, instead of a mechanical commutation system (i.e. brushes).

In a conventional (brushed) DC motor, the brushes make mechanical contact with a set of electrical contacts on the rotor (calls commutator), forming an electrical circuit between the DC electrical source and the armature coil-windings. As the armature rotates on axis, the stationary brushes come into contact with different sections of the rotating commutator.

In the BLDC motor, the electromagnets do not move. Instead, the permanent magnets rotate and the armature remains static. This gets around the problem of how to transfer current to a moving armature. In order to do this, an intelligent electronic controller replaces the brush-system/commutator assembly. The controller performs the same power distribution found in the brushed DC motor, but using a solid-state circuit rather than a commutator/brush system.

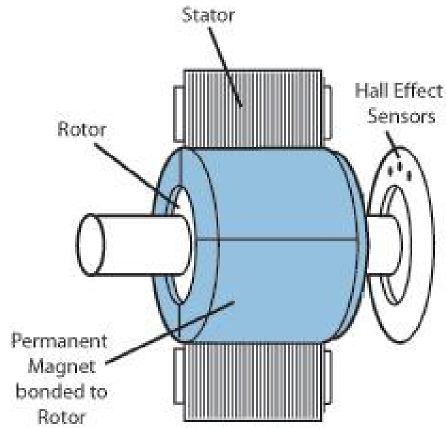

Fig. 5: BLDC motor architecture (Compter, 2007).

BLDC motors offer several advantages over brushed DC motors, including higher efficiency and reliability, reduced noise, longer lifetime (no brush erosion), elimination of ionizing sparks from the commutator, and overall reduction of electromagnetic interference (EMI). The maximum power that can be applied to the BLDC motor is exceptionally high, limited almost exclusively by heat, which can damage the magnets. BLDC main disadvantage is higher cost, due to need of complex electronic speed controllers to run.

BLDC motors are considered to be more efficient than brushed DC motors. It means that for the same input power, the BLDC motor converts more electrical power into mechanical than the brushed motor, mostly due to the absence of friction of brushes. The enhanced efficiency is greatest in the no-load and low-load region of the motor's performance curve.

Because the controller must direct the rotor rotation, the controller needs some means of determining the rotor's orientation/position (relative to the stator coils.) Some designs use Hall Effect sensors or a rotary encoder to directly measure the rotor's position. Others measure the back EMF in the undriven coils to infer the rotor position, eliminating the need for separate Hall Effect sensors, and therefore are often called "sensorless" controllers.

The controller contains 3 bi-directional drivers to drive high-current DC power, which are controlled by a logic circuit. More advanced controllers employ a DSP microcontroller to manage acceleration, control speed and fine-tune efficiency. Controllers that sense rotor position based on a back-EMF have extra challenges in initiating motion because no back-EMF is produced when the rotor is stationary. This is usually accomplished by beginning rotation from an arbitrary phase, and then skipping to the correct phase if it is found to be wrong. This can cause the motor to run briefly backwards, adding even more complexity to the startup sequence.

6. Mathematical model of BLDC motor

An integrated part of every design and implementation of high critical control system is a mathematical model. This model serves to validate control algorithms and behavior of the BLDC motor (which is a critical part of an EHA/EMA actuator) in limit states. Use of mathematical model rapidly speeds up the development cycle and enhances the overall system safety and reliability.

The mathematical model of the BLDC motor, created in the MATLAB/Simulink environment, consists of several independent blocks, which describe its real behavior. For easier orientation it can be separated into two parts - **electrical** and **mechanical**, shown in the Figure 6. For this reason it is possible to apply the model to any control circuit or complex system.

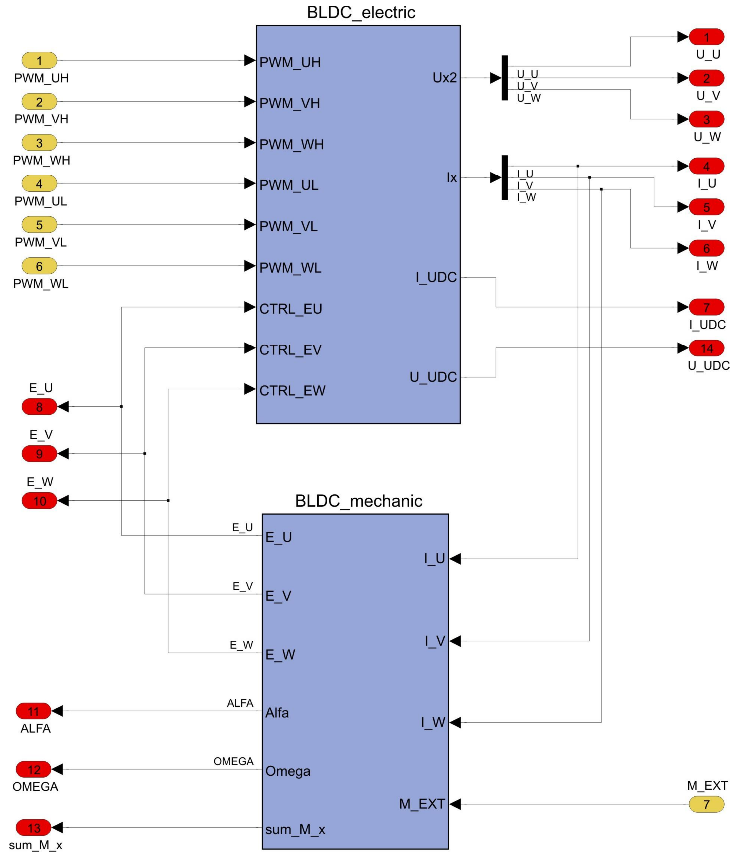

Fig. 6: Mathematical model of BLDC motor – electrical and mechanical part.

The mathematical model is designed to implement as many as possible of the parameters supplied by the BLDC motor's manufacturer. The aim is to have a model that reliably matches a real BLDC motor. Input parameters are set in special M-file, in numbers about 20 values.

The electrical part models the internal conditions and wiring of the direct current motor. It provides fundamental electrical parameters at its outputs such as currents and voltages on individual windings. The component's design parameters and appropriate driving signals from superior blocks are required as the input parameters.

The differential equations describe electrical behavior of direct current motor and are solved by numerical methods in Simulink environment. Individual phase voltages are evaluated and could be used for sensor less detection of actual rotor position.

The electrical part of the model is created from parts of the SimPower integrated environment. It can be thought of as an electrical schematic of a motor, Figure 7. Even if Simulink libraries have the better switching components, such as power MOSFET, IGBT or bipolar transistors, it was used only basic ideal switching device with inverse diode. That will dramatically decrease computation time to real value.

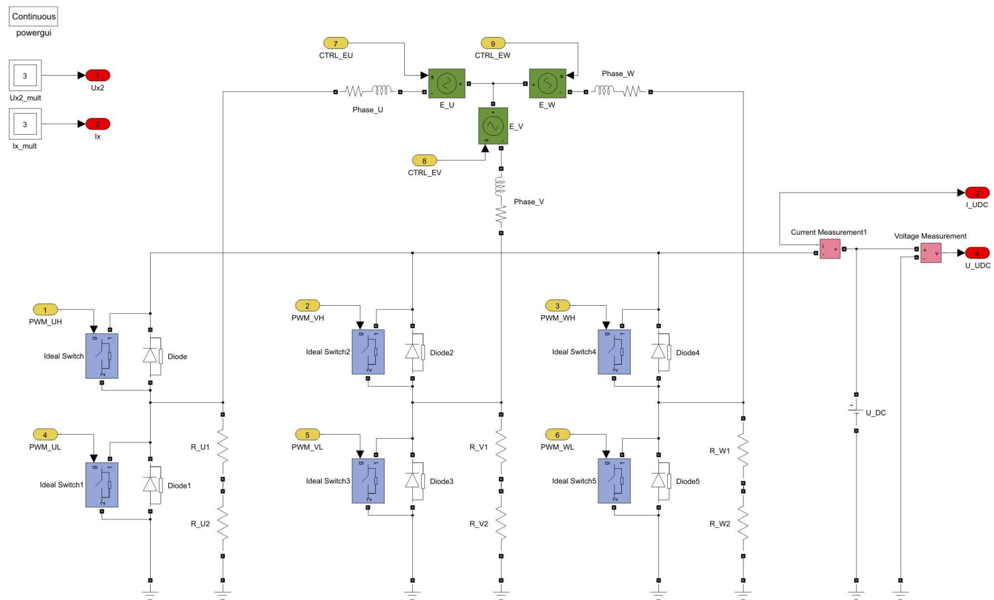

Fig. 7: Electrical part of the model with power stage.

The mechanical part Figure 8 of the model is based on equation of motion and simulates the interaction between mechanical and electrical values of the system. Actual kinetic torques of individual windings is evaluated according to input currents from the electrical part. The model also takes into account attenuation forces arising from friction during rotation or from appropriate external braking torques on the rotor shaft.

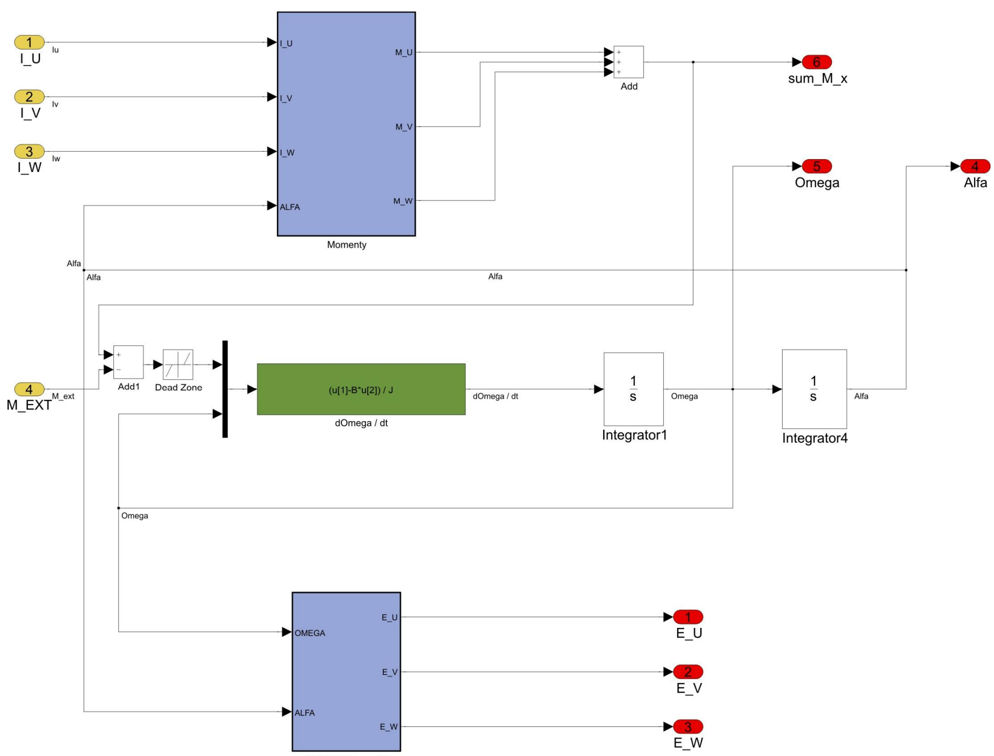

Fig. 8: Mechanical part of the model.

An important output value is the amplitude of induced voltages in particular windings. This is used for detection of the correct moment for commutation during sensor-less control conditions. These back EMF voltages are evaluated in subsystem that is depicted in the Figure 8 lower block. Integration of the equation of motion is possible to enable evaluation of instantaneous rotor position and angular velocity. This part of model is created in the Simulink environment by means of basic integrated blocks, Figure 8.

7. Control system software design

The main aim that was taken into consideration is that control system had to be portable and easy to implement on a common 16-bit MCU. Final control system is written in the C programming language and is implemented into a Microchip dsPIC MCU.

Algorithms are designed with respect to high criticality of the application, therefore no artificial methods or fuzzy control algorithms could are used. Requirements on high reliability also limit code complexity, thus the simplest software algorithms are used wherever is possible.

Software design was preceded by detailed decomposition of system requirements, interface definitions, data flow and control flow. These requirements and definitions expressively determined final form of source code. Therefore their thorough evaluation was extremely important for design of control algorithms. Proper definition and evaluation simplified software development cycle and eliminated errors caused by further implementation of additional functions.

The control algorithm is designed according to the flowchart that is shown in Figure 9. The algorithm consists of initialization part, motor start-up, closed loop control and interrupts service routines.

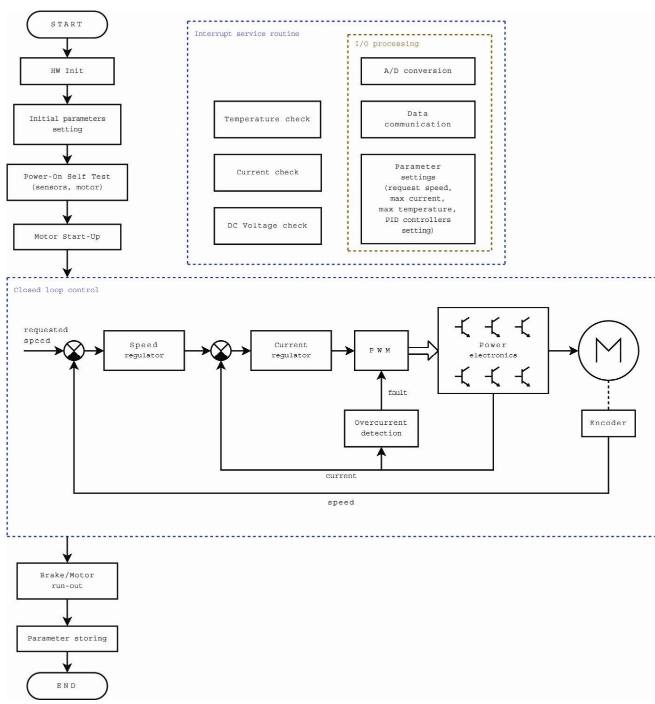

Fig. 9: Concept of the control system software design.

8. Conclusion

Intelligent EHA/EMA actuators and smart actuation systems are becoming promising technologies for future power optimized aircraft. Although their benefits in energy consumption, weight savings, easy assembly procedures and maintenance are obvious, there still remain some features whiz has to be evaluated. These features, which have to be demonstrated during the certification process, are mainly concerning the safety and reliability of the actuator.

Because of this high demand, simulation and modeling tool are widely used to accelerate the development a verification of control algorithms. As a side effect many possible system failures or limitations are found in the early stage of the project, thus the overall system reliability is increased.

The modular architecture has been proposed - the control system consists of three independent modules which perform their specific function and are exchangeable according to the customer needs.

Attention has been given also to software design considerations. The basic concept has been introduced, including the mathematical model of the controlled BLDC motor and software design principles.

Acknowledgment

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