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MODELING AND ANALYSIS OF ELECTRO-MECHANICAL FLIGHT ACTUATOR SYSTEM

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Abstract

Electro-mechanical flight actuator (EMFA) systems improve efficiency, reliability, safety, and maintainability in More Electric Aircraft (MEA) programs intended for next generation commercial aircrafts, as compared to the traditional hydraulic systems. A power-by-wire system actuation approach, based on incorporating high torque density brushless motors featuring superior characteristics, is increasingly used in the design of both primary and auxiliary flight control surfaces, improving the system performance while reducing its weight. An EMFA system based on a permanent magnet three-phase synchronous machine fed by a Variable Frequency Current Hysterisis Controlled Inverter and additionally incorporating two outer loops, a position and a velocity loop, is proposed in this work. A MATLAB Simulink/SimPowerSystems software tool is used to model the system and analyze its functionality, accuracy, stability, disturbance rejection and acceleration capabilities, for specific cases of landing and takeoff.

Intoduction

More Electric Architectures have primarily involved the use of much larger number of electromechanical actuators for primary flight and secondary controlled surfaces. Power-by-wire technology payoffs include elimination of the central hydraulic system, reduction of maintenance support, increased survivability significant reliability improvement, more efficient use of secondary power, and improve ability to turn off or reconfigure a damaged or inoperative flight control surface.

Fly-by-wire or fly-by-light control of EMFAs is executed by Flight Control Systems and is part of flight-critical vehicle components. Advanced simulation engineering software tools are used for control design, development, testing and verifying of the simulated results [1, 2]. The elimination of hydraulic and pneumatic secondary power systems will improve maintainability, increase reliability, reduce life cycle costs, increase energy efficiency and improve flight readiness. This explains why, in recent years, there has been much interest in the 'all-electric' aircraft, and its supporters have emphasized the serious consequences of hydraulic fluid loss and the weight and space disadvantage of a centralized hydraulic power distribution system, especially where there are large distances between the primary power source and the actuators. Therefore, electric surface actuation systems will only show a significant weight saving advantage, if the hydraulic system is removed completely from the aircraft [3].

Electro-mechanical actuators involve conversion of rotary motion (from an electrically powered source) into linear or rotary displacement. There are many designs of modern linear actuators and every company that manufactures them tends to have its own proprietary methods and designs. In one approach, a rotor driver is mechanically connected to a long shaft so that the rotation of the electric motor will make the shaft rotate. The shaft has a continuous helical thread machined on its circumference running along the length. Threaded onto this shaft is a nut with corresponding helical threads. The nut is kept from being able to rotate with the shaft (this often involves an interlocking of the nut with a stationary part of the actuator). Therefore, when the shaft is rotated, the nut will be driven up or down the threads depending on the direction of rotation. By fashioning linkages to the nut, this can be converted into usable linear displacement. Most current actuators are built either for fast speed, high torque capacity, or a compromise between the two.

Typical landing flaps drive system architectures of rotary motion conversion into linear displacement for flaps mechanism is [4]:

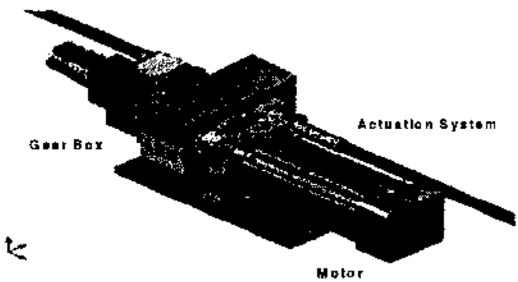

Fig.1. Landing Flap Drive System

Permanent Magnet Synchronous Machine SimPowerSystems Model Description

This paper deals with the Permanent Magnet Synchronous Machine (PMSM) model applied to drive the flap actuation system. The PMSM operates in motoring mode where positive mechanical torque is required. The electrical and mechanical parts of the machine are each represented by a second-order state-space model. The sinusoidal model assumes that the flux established by the permanent magnets in the stator is sinusoidal, which implies that the electromotive forces are sinusoidal. For the trapezoidal machine, the model assumes that the flux established by the permanent magnets is purely trapezoidal, which implies a trapezoidal electromotive forces waveform [5].

The sinusoidal model electrical system implements the following equations in $d-q$ transformed plane:

$$\frac{di_d}{dt} = \frac{1}{L_d} u_d - \frac{R}{L_d} i_d + \frac{L_q}{L_d} p\omega_r i_q,$$

$$\frac{di_q}{dt} = \frac{1}{L_q} u_q - \frac{R}{L_q} i_q + \frac{L_d}{L_d} p\omega_r i_d - \frac{\lambda p\omega_r}{L_q},$$

(1) $$T_e = 1{,}5p\left(\lambda i_q + \left(L_d + L_q\right)i_d i_q\right),$$

where L_q, L_d - axis inductance, R - stator windings resistance, u_d, u_q - axis voltage, ω_r - rotor velocity, λ - amplitude of the flux induced by the permanent magnets of the rotor in the stator phases, p - number of pole pairs, T_e - electromagnetic torque.

Trapezoidal model electrical system in a, b, c frame:

$$\frac{di_a}{dt} = \frac{1}{3L_S}\left(2u_{ab} + u_{bc} - 3R_S i_a + \lambda p\omega_r\left(-2\phi_a' + \phi_b' + \phi_c'\right)\right),$$

$$\frac{di_b}{dt} = \frac{1}{3L_S}\left(-u_{ab} + u_{bc} - 3R_S i_b + \lambda p\omega_r\left(\phi_a' - 2\phi_b' + \phi_c'\right)\right),$$

(2) $$\frac{di_c}{dt} = -\left(\frac{di_a}{dt} + \frac{di_b}{dt}\right), \quad T_e = p\lambda\left(\phi_a' i_a + \phi_b' i_b + \phi_c' i_c\right),$$

L_S - stator windings inductance, R - stator windings resistance, i_a, i_b, i_c - a, b, c phase currents, $\phi'_a, \phi'_b, \phi'_c$ - a, b, c phasc electromotive forces, u_{ab}, u_{bc} - a, b and b, c phase to phase voltages.
Mechanical system:

$$(3) \qquad \frac{d\omega_r}{dt} = \frac{1}{J}\left(T_e - F\omega_r - T_m\right), \; \frac{d\Theta}{dt} = \omega_r ,$$

J - inertia of rotor and load, F - friction of rotor and load, Θ - rotor angle position, T_m - load torque.
The sinusoidal machine is simulated in the $d-q$ rotor reference frame and the trapenzoidal machine in the abc frame. Stator windings are connected in wye to an internal neutral point.

Variable Frequency Current Hysterisis (VFCH) Controlled Inverter SimPowerSystems Model

A DC / AC inverter is represented by current comparison blocks and full-bridge inverter. It uses ideal switches and antiparallel diodes and also demonstrates the VFCH Control provided by current comparison between reference and actual values. Six pulses are generated for a three-arm bridge.

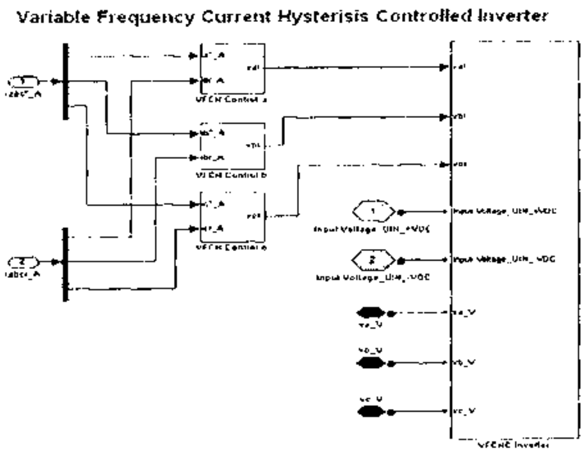

Fig.2. Variable Frequency Current Hysterisis Controlled Inverter - Layer 1

Comparion blocks include also low pass filters to eliminate high frequency noise. The hysteresis modulation is a feedback current control method where the motor current tracks the reference current within a hysteresis band. The following figure shows the operation principle of the hysteresis modulation. The controller generates the sinusoidal reference current of desired magnitude and frequency that is compared with the actual motor line current. If the current exceeds the upper limit of the hysteresis band, the upper switch of the inverter arm is turned off and the lower switch is turned on. As a result, the current starts to decay. If the current crosses the lower limit of the hysteresis band, the lower switch of the inverter arm is turned off and the upper switch is turned on. As a result, the current gets back into the hysteresis band. Hence, the actual current is forced to track the reference current within the hysteresis band.

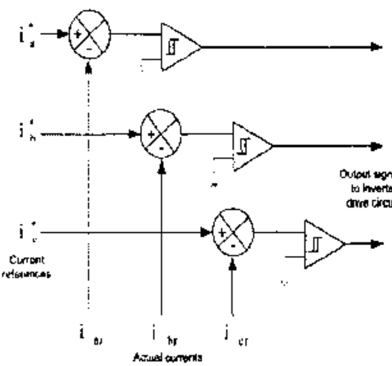

Fig. 3. Variable Frequency Current Hysterisis Control Scheme

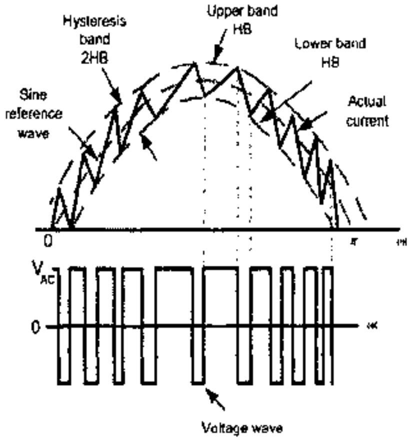

Fig. 4. Voltage Wave Control Input Signal Generation

The inverter is designed to accomodate Dead Zone T_d _s to eliminate simultaneously turning on the switches in a, b or c phase (if both switches in one phase are on, it produces short current in that phase, Fig.5). Each ideal switch consists of a diode to keep the current flow in the desired direction and also anti parallel diode (free wheeling diode) to ensure current flow for inductive loads.

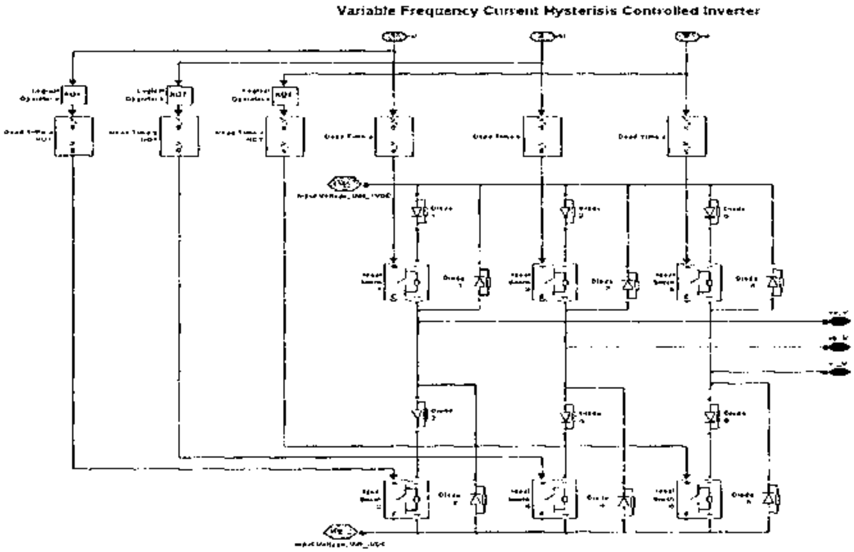

Fig. 5. Variable Frequency Current Hysterisis Controlled Inverter - Layer 2

Electro-Mechanical Flap Actuation SimPowerSystems Model

Flaps generally increase the camber of the wing and therefore increase the wing's lift. This allows a slower speed without stalling. Effects of the flap also permit steeper glide angle in the landing approach. The flap is a hinged surface attached to the trailing edge of the wing.

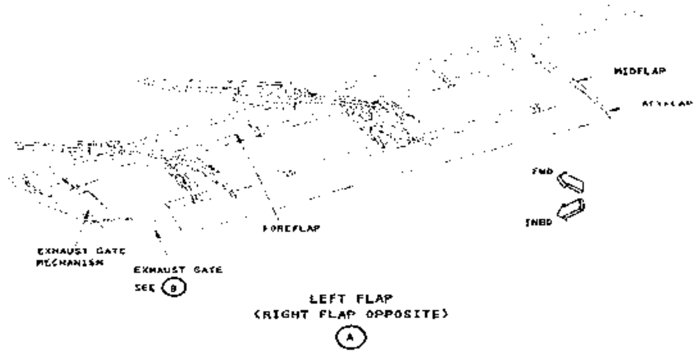

Fig.6 Trailing Edge Flaps Extracting

Flaps on both wings move in unison in response to the flight deck control input. When the flaps are not is use, they are stored as part of the trailing edge of the wing. The slotted flap is equipped with tracks, rollers, or hinges of a special design. During operation, the flap moves downward and rearward away from the position of the wing. The opened slot allows a flow of air over the upper surface of the flap to streamline the airflow and to improve the efficiency of the flap [6].

This paper deals with a high-lift device as an integrated model which simulates an Electro-Mechanical Flight Actuator System as a Landing Flap Drive System (Fig.7). A Synchronous Motor is fed by the VFVHC Inverter. Input parameter is Reference Flaps Position_ F _grade which starts executing the retracting or extending flap mechanism. Position and Speed PI Controllers are used and final error signals enter the $dq2abc$ transformation block. Measured Rotor Angle_ Θ _rad, Actual Flaps Position_ F_c _grade and Rotor Speed_ ω_m are the control loop feedbacks to Position and Speed Controller and $dq2abc$ calculation block:

$$i_a^* = i_{qref\_A}\cos(\Theta_e) + i_{dref\_A}\sin(\Theta_e) + i_{oref\_A},$$

$$i_b^* = i_{qref\_A}\cos\left(\Theta_e - 2\frac{\pi}{3}\right) + i_{dref\_A}\sin\left(\Theta_e + 2\frac{\pi}{3}\right) + i_{oref\_A},$$

(4) $$i_c^* = i_{qref\_A}\cos\left(\Theta_e + 2\frac{\pi}{3}\right) + i_{dref\_A}\sin\left(\Theta_e - 2\frac{\pi}{3}\right) + i_{oref\_A}.$$

Calculated i_a^*, i_b^*, i_c^* are compared with measured Stator Currents_ i_{ar}, i_{br}, i_{cr} and the result is processed by Variable Frequency Current Hysterisis Control (Fig.2, 3).

The Permanent Magnet Synchronous Machine has load torque input represented by air drag doing the extending or retracting process. Circular motion is transformed to linear by:

(5) $$F_c = \int\frac{\omega_m r}{p},$$ r - radius of single transmission.

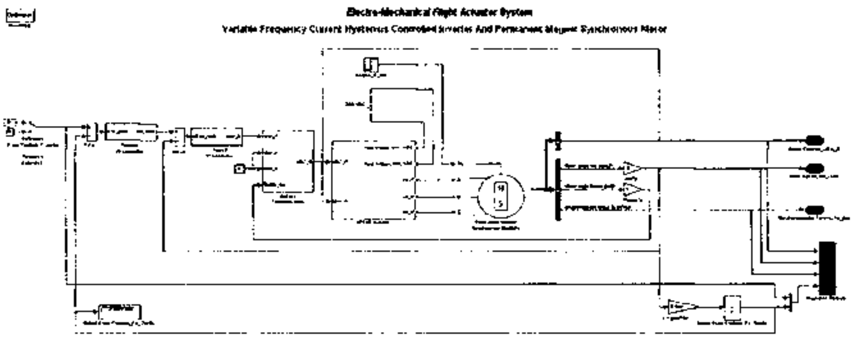

Fig. 7. Variable Frequency Current Hysterisis Controlled Inverter - Layer 2

Electro-Mechanical Flap Actuator Simulation Results

In this paper, forward and backward movement of the flap control lever is transferred directly by fly-by-wire signals as Reference Flaps Position. Landing flap functionality in extracting mode is displayed in Fig. 8. Reference Flap Position has been increased by step-step position function to reach the final extended position of 40 degrees. Stator currents, rotor speed and actual flaps position involving the load torque to the synchronous machine is shown. Full flaps extension is finished in 3,2 s.

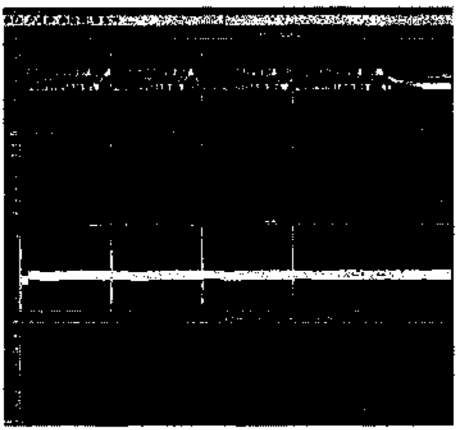

Fig. 8. Landing Flaps Extending (0 - 40 degrees)

Fig. 9 shows detail of landing flap extension from 20 to 30 degrees and the permanent magnet synchronous machine accelerating process: VFCHC Inverter stator currents and speed control. When 30 degrees position is reached, the synchronous machine is producing torque to oppose only the input load torque and remain in same position at zero rotational speed.
Backward movement of flaps - retracting is demonstrated in Fig. 10., the synchronous machine moves in opposite direction, with the same input torque profile and currents corresponding to acceleration profile.

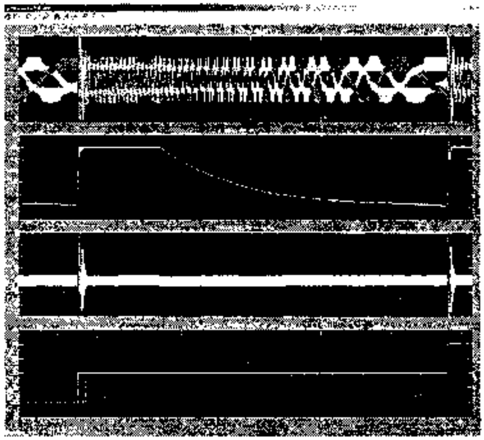

Fig. 9. Landing Flaps Extracting (20 - 30 degrees)

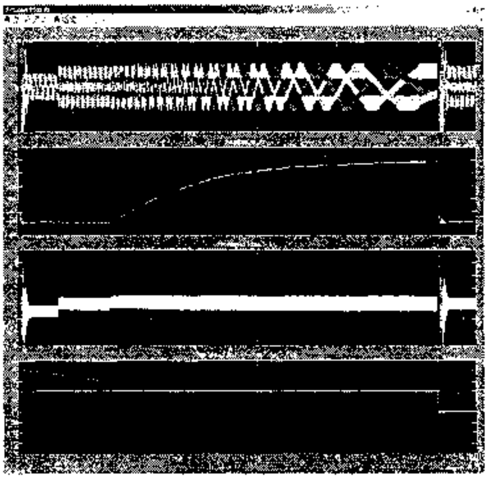

Fig. 10. Landing Flaps Retracting (40 - 30 degrees)

Conclusion

The advantages of using Electro-Mechanical Actuating Systems have been claimed for control surface applications. Electrical machines can execute accurately and quickly either multiple functions or single tasks. This paper has demonstrated the application of SimPowerSystems toolbox of MATLAB/Simulink for actuating systems, including control, analysis, integration, and verification. Extending and retracting operation modes of landing flap actuating system are demonstrated within a power optimized concept.

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МОДЕЛИРАНЕ И АНАЛИЗ НА ЕЛЕКТРОМЕХАНИЧНА СИСТЕМА ЗА АКТИВАЦИЯ НА ПОЛЕТА

М. Хичар

Резюме

Електромеханичните системи за активация на полета (EMFA) подобряват ефикасността, надеждността, безопасността и възможностите за поддръжка на програмите MEA, предназначени за търговски

въздухоплавателни средства от следващо поколение, в сравнение с традиционните хидравлични системи. Методът за активация чрез система с проводниково захранване, основаващ се на използването на безчеткови двигатели с висока степен на усукване, които притежават по-добри характеристики, се използва все по-често в разработката както на основни, така и на спомагателни повърхности за контрол на полета, подобрявайки к.п.д. на системата и намалявайки теглото й. В работата се предлага EMFA система, основаваща се на трифазен синхронен двигател с постоянен магнит, захранван от променливо-честотен инвертор с токово-хистерезисно управление, включващ и два външни контура – позиционен и скоростен. За моделиране на системата и анализ на нейната функционалност, точност, устойчивост, защита от смущения и възможности за ускоряване в конкретни случаи на кацане и отлитане е използвано програмното средство MATLAB Simulink/ SimPowerSystems.