AN ANALYSIS OF ELECTRO – HYDROSTATIC ACTUATORS IN MORE ELECTRIC AIRCRAFTS

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Abstract — The aim of this study is to evaluate the possibility of using distributed electrically powered actuator systems instead of a centralized hydraulic system composed of set of distribution pipes, for aircrafts' primary control surfaces actuation. A simulation model is developed to describe an electro-hydrostatic actuator dynamic behavior and preview its interaction with other systems. This model is included in a closed loop to command a primary surface. The closed-loop design is developed based on an algorithmic method, which utilizes a Genetic Algorithm (GA) to find the controller gains. In addition, a more electric actuation architecture is proposed and an comparison with the conventional option for an airplane design's case study is performed through an engineering analysis.

Keywords — electro-hydrostatic actuator, flight control actuation, more electric aircraft, engineering analysis.

Resumo — O objetivo deste estudo é avaliar a possibilidade de usar sistemas eletricamente potenciados na atuação de superfícies primárias de aeronaves ao invés de sistemas hidráulicos centralizados. Um modelo de simulação é desenvolvido para descrever o comportamento dinâmico de um atuador eletro – hidrostático e prever sua interação com outros sistemas. Esse modelo é incluído numa malha fechada de controle para comandar uma superfície primária. O projeto da malha fechada é desenvolvido baseado em um método algorítmico, que utiliza um Algoritmo Genético para achar os ganhos do controlador. Em adição a isso, uma arquitetura de atuação mais elétrica será proposta e comparada com a opção convencional para estudo de caso de projeto de um avião, através de uma análise de engenharia.

Palavras-chave — atuador eletro-hidrostático, controle de vôo, atuadores, análise de engenharia.

1 Introduction

The competition in aviation business is growing continuously. It motivates the aircraft manufacturers to constantly search for ways to answer the demands of the market for a better service for passenger comfort, decrease operational cost and also safety, dispatchability and reliability improvements.

The concept of a More Electric Aircraft (MEA) means the elimination of as many hydraulic, pneumatic and mechanical power sources as possible, replacing them with electric power sources. A philosophy of design in this sense can reach goals as a reduction on weight and direct operating cost, and an increase in reliability and performance.

However, the gains claimed by MEA technology depend on a new architecture concept. This study aims to give a better look in the MEA concept applied to the aircraft flight control actuation system. The understanding of this system will be accomplished by modeling a more electric actuator and performing a control design; besides that, a more electric architecture is proposed and discussed using an engineering analysis.

2 System description

There are two major types of electric powered flight control actuation in consideration for a more electric aircraft: Electro-Mechanical Actuator (EMA) [2], which replaces the hydraulics by an electric machine, gearbox and a screw mechanism; and the Electro-Hydrostatic Actuator (EHA), which utilizes a motor-pump to produce hydraulic power to displace the piston.

It is noticed that the selection of a EMA or a EHA tends to the second one. A few reasons for that will be listed. The use of hydraulic to source the actuators of primary surfaces (elevator, rudder and aileron) is already in use in the majority of commercial airplanes nowadays. This source of power is widely known, and there is a wealth of data and know-how within traditional suppliers. EHA would take advantage of this. The possibility of producing high torque quickly also favors EHA. The flutter damping requirement still has to be solved in EMA. So, this study will focus on EHA as it seems as a more promising option for the next generation of primary surfaces actuation.

There are two main concepts regarding EHA. First is the EHA-FP with fixed displacement pump and a speed controlled electric motor.

On EHA-FP model, a variable-speed electric motor is used to drive a fixed-displacement hydraulic pump, which in turn, powers a conventional hydraulic piston jack. Change in direction is achieved by the use of a bidirectional motor. The manufacturing and the maintenance of this component is simpler than a movable mechanical component such as a swash plate that is the functional base of the next actuator's type description.

The second model is the EHA-VP, with a variable displacement pump and an electric motor rotating at constant speed.

The EHA-VP model uses a pump rotating at constant speed. A separate control mechanism varies the swash plate angle within the pump, and it is therefore able to continuously vary the hydraulic fluid flow to the actuator. When the swash plate passes through the over-center position, hydraulic fluid flow is reversed, thus changing the actuator's direction. In contrast to the EHA-FP model, EHA-VP actuators do not need high-power electronic controllers for motor control. Typically AC induction motors are used. They are connected directly to the aircraft AC supply and run synchronously with the AC supply frequency. EHA-VP thermal characteristics are less sensitive to load and high-frequency demands. If necessary, continuous forced cooling can be easily introduced because the motor is continuously running.

Among the two possible technologies for EHA, the broader case to be analyzed is EHA-FP. First, the electrical system will receive greater interference from the power electronic demanded to vary the electric motor speed; secondly, it also requires more attention regarding thermal dissipation. However, the electrical and thermal modeling characteristics of EHA are not going to be covered in this study.

3 Modeling and simulation

3. 1 Mathematical modeling for control

An effort on mathematical modeling of the equipment is developed in this section, as a manner to help describing the EHA, preview its behavior, interaction with other systems, and control system design. A few hypotheses were considered before modeling the system. First, the aircraft's electric system has infinite power and would not allow any variation on the current delivered to the EHA. The EHA would work only in the normal operation mode. And, it was considered that, no backlash could interfere severely on the EHA's functioning.

Consider a schematic of an EHA-FP system as represented in Figure 1. A system graph of the EHA-FP representation is shown in Figure 2 modeling the elements connections and the energy transformations through the components [3-5].

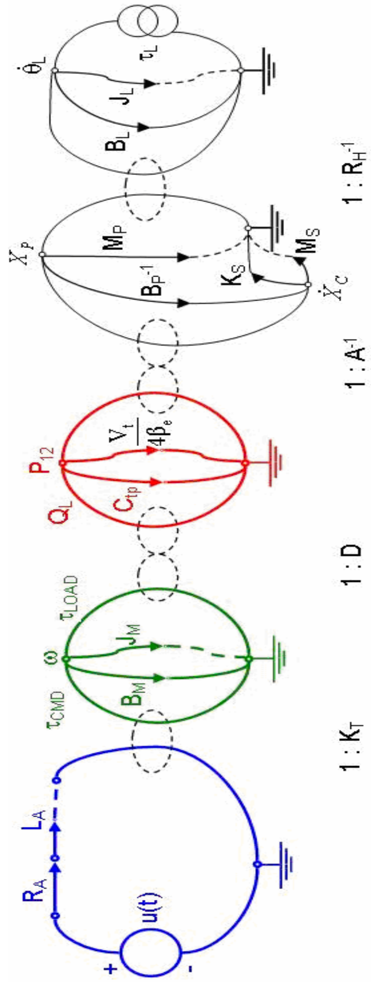

Figure 2: EHA system graph

The sub-graph in blue represents the armature circuit of the electrical motor model, where

u(t):	Input voltage [V]
R_A:	Motor's resistance [Ω]
L_A:	Motor's inductance [H]
K_T:	Electromotive force constant [N.m/A]

The circuit in green represents the mechanical transformation in the motor conjugated with the inertia of the fixed displacement pump, where

ω:	Rotor angular speed [rad/s]
J_M:	Rotor plus pump moment of inertia [kg.m.s2]
B_M:	Viscous mechanical damping [kg.m.s]
τ_{CMD} :	Torque developed by the rotor [N.m]
τ_{LOAD} :	Torque due to the differential pressure of the fluid [N.m]
D:	Pump volumetric displacement [m^3/rad]

The circuit in red represents the hydraulic connection between the pump and the piston, where

Q_L: Load flow in and out from the piston [m^3/s]

P_{12}: Load (net) pressure on piston [N/m^2]
C_{ip}: Internal or cross-port leakage coefficient of motor [$m^4.s/kg$]
C_{ep}: External leakage coefficient of motor [$m^4.s/kg$]
C_{tp}: Total leakage of piston $C_{tp}=C_{ip}+C_{ep}/2$ [m.s]
β_e: Effective bulk modulus of system [N/m^2]
V_t: Total volume of fluid under compression in both chambers [m3]
$\frac{V_t}{4\beta_e}$: Fluid capacitance due to compressibility
A: Piston's area [m^2]

The sub-graph in black represents the mechanical elements and variables on the piston and flight control surface, where

M_S: Actuator mass [kg]
M_P: Piston mass [kg]
B_P: Piston viscous damping (friction) [kg.m]
K_S: Stiffness coefficient of the connection between actuator and aircraft [kg/s2]
$\dot{X}_P$: Piston speed [m/s]
$\dot{X}_C$: Actuator speed [m/s]
B_L: Flight control surface damping [kg.m.s]
J_L: Flight control surface inertia [$kg.m.s^2$]
θ_L: Flight control surface angular position [rad]
τ_L: Aerodynamic hinge moment reflected [N.m]

A systematic approach allows obtaining a state-space model from its system graph, which is presented in Equation 1.

3. 2 Simulation block diagram

The model developed was implemented in a MATLAB/Simulink model as shown in Figure 3. All the numeric values used in the simulations were defined through extrapolation of real values from a commercial aircraft. The EHA in study is projected to supply a rudder actuator for a 132 passenger airplane and the main values to this case study are presented in Table 1.

Pressure [psi]	3000
Stroke [m]	0.15
Time [s]	1.00
Speed [m/s] no load rate	0.15
Force [N] stall load	45000
Power [W]	6750
Piston Diameter [m]	0.053
Fluid flow [gpm]	5.17

Table 1: EHA data

Closed-loop design [1]

The EHA model is intended to be used in closed-loop to allow the output to follow with adequacy the reference and reject step output disturbances. The operational requirements for this actuator are to achieve at least the same behavior of a conventional electro – servo valve.

In this work, the closed-loop design aims are to choose which signals to feedback and to adjust the controller gains. The options of signals to feedback are: piston displacement (X_p), flight control surface angular position (θ_L), load pressure ($P_L = P_{12}$), motor speed (ω) and motor current (i). However, more variables than necessary to be feedback, more complex and costly become the system implementation. An approach to answer to this issue was the selection of two variables to feedback: one related to EHA output and one related to motor output. The variable chosen related to EHA output is the piston displacement (X_p), because it requires a simpler measurement system comparing to the surface angular position, but yet represents the final objective of the control design; the variable related to the motor is the speed (ω), because it captures the behavior of the motor electric circuit and also includes information of pump's rotation. Obviously, if these signals had been shown inadequate for attaining the requirements, another set of signals for feedback would be tried. The sensors of these variables were modeled as simple gains; the values used in this work are 63 V/m for the LVDT measuring the piston displacement and $4x10^{-3}$ V/(rad/s) for the tachometer.

The next step is to determine the values for the control block. This system already has a pole in the origin (type 1 system), so a constant (step) reference will be followed with no steady-state error by adjusting the feedback gains appropriately. The same is valid for rejecting step output disturbance for this control configuration. An algorithmic method was utilized to determine the gains k1 and k2, referring to X_p and ω respectively, of the control block. Many design methods could be utilized to obtain the controller gains. It was chosen a searching method through the minimization of a cost function. The cost function included output specifications and minimization of control energy. Besides that, through a searching method using the simulation model [Figure

3] as a manner to evaluate the cost function, it was possible to consider in the design saturations of pump's flow, motor's current and piston's displacement. The searching algorithm used was a Genetic Algorithm [7].

The solution for the problem provided the pair of gains:

$$k1 = 0.1313$$
$$k2 = 7.3859$$

The parameters used to define the genetic algorithm are listed in Table 2.

3.4 *Closed-loop responses* [1]

The closed loop responses are shown in this section. The saturation in the motor's current and in the pump flow was inserted in the system simulation in order to have a more faithful model.

The input for the system is a step of 0.05253m to the piston's displacement, which means a deflection of 25° for the surface in an altitude of 12497m (41000 ft).

Parameter	**Value**
Number of population	40
Number of generations that max value remains constant	20
Number of mutation children (Gaussian)	3
Number of mutation children (Random)	3
Number of elitism children	1
Minimal possible value of variables	0
Maximum possible value of variables	30

Table 2: GA parameters

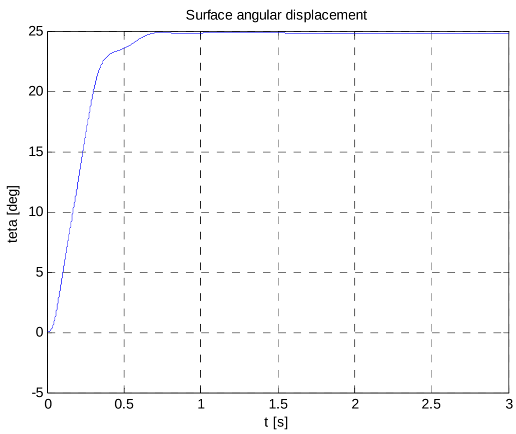

Figure 4: Surface's angular position

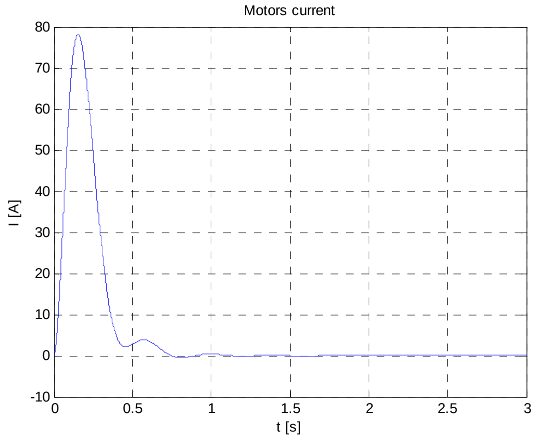

Figure 5: Motor current

The result presented in the Figure 4 is obtained for following the reference from the neutral position until the maximum deflection of the surface. The surface's angular position is the output of the system after the piston displacement. The graph in Figure 5 is the current demanded by the motor to provide the pressure necessary to produce the piston displacement. It was also implemented a simulation of an external aerodynamic load step. This external load happens at 1.5s and tests the disturbance rejection of the control system. It can be verified through the graphs that, despite a variation of 10% in the load, the controlled variable does not show a noticeable change.

4 Engineering Analysis [1]

After modeling the EHA, this section will propose a more electric actuation architecture where the EHA could be more advantageous than the conventional actuation architecture for a case study of a hypothetical airplane of 132 passengers.

Notice, however, that if all the consumers use EHA the exchange would not save weight. It is intuitive through the comparison of a lighter weight of one centralized pump opposed to many distributed pumps, as the last architecture will combine many efficiencies resulting in a smaller overall efficiency.

The conventional system permits that different loads share the same centralized hydraulic system. The pressurized lines transport the hydraulic energy from the central pump through the aircraft until each load.

An actuation architecture which uses hydraulic and electric power is proposed here to not penalize the weight heavily, but yet attains the benefits of more electric technology.

4.1 *Actuation architecture possibilities*

The actuation architecture is designed based on safety requirements. Loss of aircraft controls shall be extremely improbable (less than 10^{-9} per flight hour) to comply with certification requirements. So, if hydraulic power is required for this purpose, complete loss of hydraulic power shall be extremely improbable.

After consulting aeronautical equipment manufacturers, it was concluded that the conventional technology presents a failure rate in the range of $2x10^{-5}$ for hydraulic system of an aircraft in the size of this case study. So, with this failure rate, it would be enough to use two hydraulic systems. The combined failure rate is $4x10^{-10}$ and it surpasses the minimal requirements of safety mentioned. It is only because of the safety requirement of common mode failure that the architecture includes an emergency system to power at least one primary control surface on each axis of aircraft's motion. So, accomplishing the requirements of safety, the typical actuation architecture is divided in three hydraulic systems.

Systems 1 and 2 present various consumers distributed all over the aircraft. Some of the consumers such as the landing gear and thrust reverser require high power in a small period of the flight. The replacement of all the loads in these systems would require very heavy EHA mainly for landing gears and thrust reverser even though they would not be used during most part of the flight. On the other hand, the third actuation system is responsible only for moving a few primary control surfaces, which are: one actuator on rudder, one actuator on elevator and two actuators for ailerons.

The third actuation system typically has two pumps connected to the electric system. The more electric actuation architecture proposed is to substitute only this third system. It would eliminate the third hydraulic system, and use instead electrical cables to transmit energy directly to each surface which would use an EHA to move the primary surfaces. The final architecture is presented in Figure 6.

4.2 *Weight*

The only way to compare the impact on weight for this new technology is comparing it in terms of component with the conventional architecture. So, as a case study, it was performed a tabulation of components for the third actuation system for a commercial transport airline of 55 ton of MTOW (132 passengers) in a conventional architecture and in the more electric architecture.

The more electric architecture proposed provides the same primary flight control surfaces. The final results are compiled in Table 3. The weight of the conventional architecture is 4kg lighter than the more electric architecture, such a difference is in the error range of this estimation. However, it is reasonable to say that both architectures would have a similar weight value. The next step is to evaluate the safety aspects of this proposal.

Conventional	Hydraulic system equipment	48.51	126.12
	Hydraulic transport elements	9.87	
	Equipment fluid weight	19.74	
	Conventional actuators	48.00	
More electric	Electrical components	2.20	130.20
	Electrical cables	8.00	
	EHA	120.00	

Table 3: Weight comparison (kg)

4. 3 *Safety / MTBF*

Aeronautical equipment manufacturers states that, typically, the hydraulic system 3 has an overall failure rate of $2x10^{-5}$ per flight hour for an airplane such this case study. The failure mode with the greater impact on the hydraulic system reliability is leakage. The other equipments on the hydraulic system have a smaller failure rate of around $1x10^{-7}$ per flight hour. The new proposal should be at least equivalent in this aspect to allow a substitution.

The more electric architecture uses EHA and electric components such as harness, switches and relays. The most important impact on reliability will be given by the EHA. The state of the art for EHA provided by a manufacturer consulted presents a Mean Time Between Failures (MTBF) of 9740 flight hours. A possible extrapolation is to consider a failure rate in the order of $1x10^{-4}$ to EHA. Despite of the individual worst failure rate, the integration of each EHA minimize opportunities for common cause failures; they are connected to the electric system in parallel, and one EHA failure does not impact the others EHA, as it would occur in leakage failure.

4.4 *Thermal aspects*

This topic deals with one major difference between the conventional hydraulic actuator and the EHA choice: the thermal issue. The dissipation of heat is distributed all over the aircraft through the distribution lines for the conventional system. The fluid passes inside all the equipment and is re-circulated. On the other hand, the dissipation of heat on EHA is limited to the volume it occupies.

The worst case for EHA is holding a constant load. The current technology for EHA-FP requires a motor providing constant torque to hold a constant load. In this scenario the pump leakage and the constant current inside the motor generate heat. The actuator is typically placed on closed compartments with poor ventilation and poor heat exchange. It is necessary to provide alternative ways to dissipate the heat.

5 Conclusion

This work started with a discussion of the benefits of the more electric aircraft initiative in regard to reduction of operating costs and development costs. It presents a possible architecture in which those improvements could be achieved through the use of an Electro-Hydrostatic Actuator (EHA) in an airplane design case study.

A simplified model of an EHA-FP (Fixed Pump displacement) is presented. This model is included in a closed loop to control a primary surface model. The analysis of the equipment and its interaction with all the other systems is a tool for the next generation of aircraft design. The design of the closed loop gains were done algorithmically by a Genetic Algorithm.

The last section is a system engineering analysis of the more electric architecture proposed. This architecture replaces only the aircraft actuation third system (emergency system) and, then, it can achieve design, manufacturing and maintenance simplification without increasing the overall weight. It was shown that for a 132 passenger airplane, the weight of a more electric architecture would be only 4 kg heavier.

A more detailed presentation and analysis of this subject can be found in [1].

6 References

[1] Barbosa Jr., Francival. Analysis of electro - hydrostatic actuator in more electric aircrafts. Master's dissertation. Department of Mechanical Engineering. São José dos Campos: ITA, 2006.

[2] Torabzadeh-Tari, M. Analysis of electro-mechanical actuator systems in more electric aircraft applications. School of Computer Science. Electrical Engineering and Engineering Physics. Sweden: KTH, 2005

[3] Liu, R. Nonlinear control of electro-hydraulic servo systems: theory and experiment. (Master of Science) – Department of Mechanical Engineering. Illinois(USA): University of Illinois at Urbana-Champaign, 1998.

[4] Navarro, R. Performance of an electro-hydrostatic actuator on the F-18 systems research aircraft. USA: NASA, 1997.

[5] Kang. K.; Pachter, M.; Houpis, C.; Rasmussein, S. Modeling and control of an electro-hydrostatic actuator. USA: Air Force Institute of Technology, 1994.

[6] Stephen, L. Botten; Whitley, C.; King, A. Flight Control Actuation Technology for Next-Generation All-Electric Aircraft. Technology Review Journal. Millennium Issue, 2000

[7] GOLDBERG, D. *Genetic Algorithms in Search. Optimization. and Machine Learning*. Boston: Addison-Wesley, 1989.

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\begin{bmatrix} \dot{i} \\ \dot{\omega} \\ \dot{x}_P \\ \ddot{x}_P \\ \dot{x}_C \\ \ddot{x}_C \\ \dot{\theta} \\ \ddot{\theta} \\ \dot{P} \end{bmatrix}
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\begin{bmatrix}
-\frac{R_A}{L_A} & -\frac{K_E}{L_A} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\frac{K_T}{J_m} & -\frac{B_m}{J_m} & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{D_m}{J_m} \\
0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & -\frac{K_h}{M_P} & -\frac{B_P}{M_P} & 0 & \frac{B_P}{M_P} & \frac{K_h \cdot R_h}{M_P} & 0 & \frac{A}{M_P} \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & \frac{B_P}{M_S} & -K_S & -\frac{B_P}{M_S} & 0 & 0 & -\frac{A}{M_S} \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\
0 & 0 & \frac{K_h}{J_L \cdot R_h} & 0 & 0 & 0 & -\frac{K_h}{J_L} & -\frac{B_L}{J_L} & 0 \\
0 & \frac{D_m \cdot 4 \cdot \beta}{Vt} & 0 & -\frac{4 \cdot \beta \cdot A}{Vt} & 0 & \frac{4 \cdot \beta \cdot A}{Vt} & 0 & 0 & \frac{4 \cdot \beta \cdot C_{tp}}{Vt}
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Equation 1: *EHA state – space model*

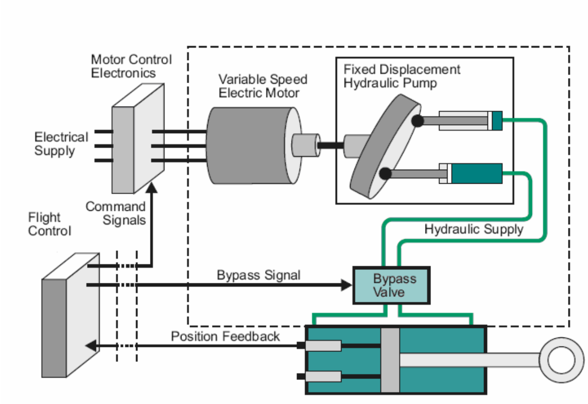

Figure 1: EHA-FP System [6]

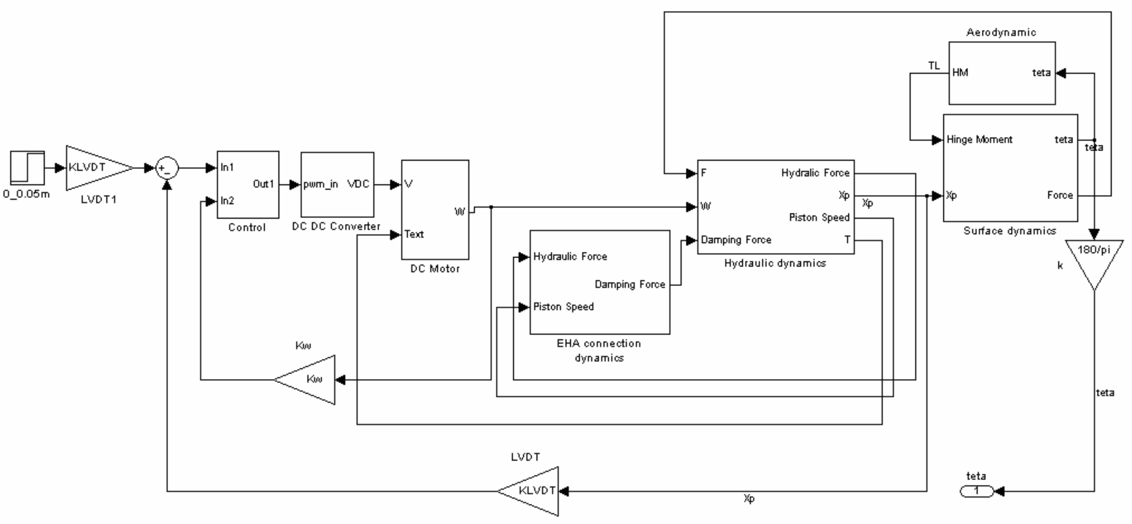

Figure 3: EHA in closed loop simulation model

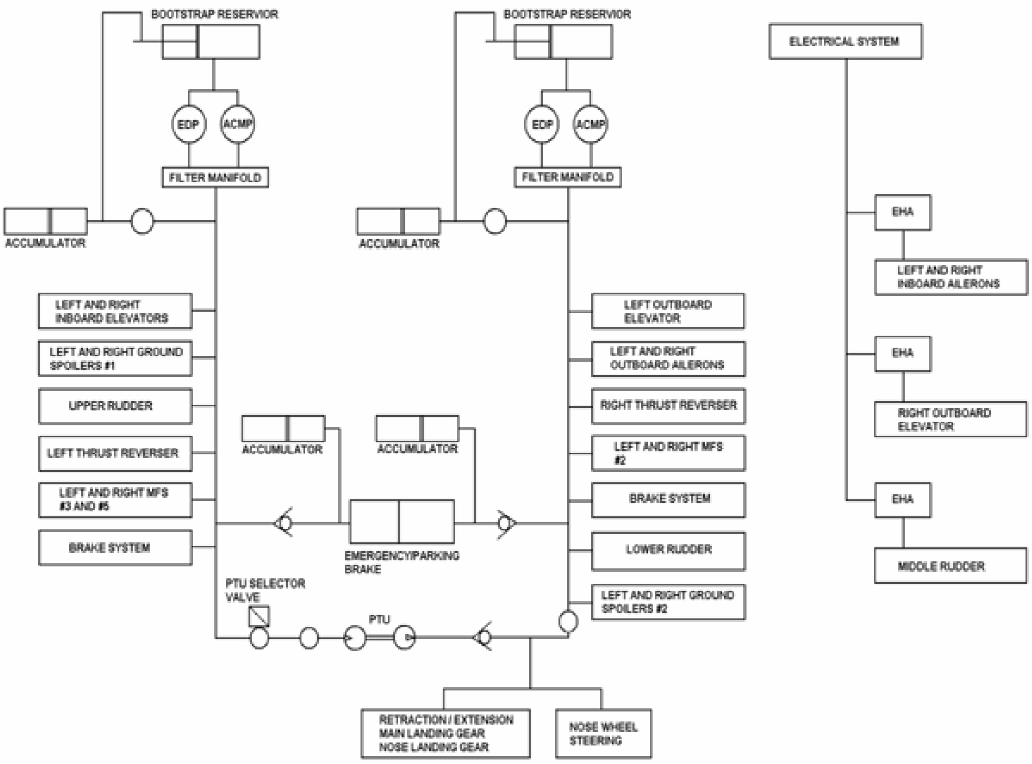

Figure 6: More electric architecture