


Review on electro hydrostatic actuator for flight control

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ABSTRACT

Electro Hydrostatic Actuator (EHA) is an emerging aerospace technology that aims at replacing centralised hydraulic system by a self-contained and localised direct drive actuator system. EHA has become an important part of modern flight control systems due to the increased efficiency, reduced leakages and lower overall weight compared to conventional hydraulic systems. This paper reviews literature (in English language only) published in the period 1990 to 2015 and available at major technical university libraries or e-journals. It examines the advantages, limitations and possible configurations of the EHA. The paper also includes control strategies, reliability and fault tolerant techniques along with the thermal aspects of the EHA system. EHA is a multi-domain system consisting of electrical, mechanical, hydraulic and control system. It is treated as a mechatronic system and review of publications related to multi-disciplinary modelling/simulation approaches have been presented in the paper. The various issues in design optimisation of EHA for flight application are elaborated. The review concludes by summarising the scope for further research in the area of redundancy strategies and approaches for integrated vehicle health management.

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1. Introduction

Actuation of flight surfaces in aircraft have evolved over the last century from systems using simple mechanical linkages actuated by the pilot to complex electronic systems that manoeuvre large loads and have some form of redundancy. In the previous century, the elimination of mechanical linkages and replacing them with electrically controlled valves had, led to the concept of Fly-By-Wire (FBW) actuation system. Over the last few decades the performance demands for flight surface actuation have increased and led to the desire of replacing the FBW actuation system with Power-By-Wire (PBW) actuation system. The latest form of flight surface actuation uses PBW systems, which are modular, lower in weight and fault tolerant actuators embedded in the flight surface that require only the attachment of power and control wires. The need of PBW actuation system for the next generation all-electric aircraft concept has been explained by Botten *et al.* (2000). Croke and Herrenschildt (1994) have attempted to bring out the status and capability of past, present and planned development aimed to support the PBW initiatives. Alden (1991, 1993) has summarised the results of investigation on PBW till the 90's and brought out a broad mix of electrical actuation concepts which have been evaluated.

PBW actuation systems have been developed to perform the functions of flight control systems. Flight

control systems on an aircraft are classified into two categories: primary flight control system and secondary flight control system. Primary flight control system in an aircraft controls all components that safely guide an airplane during flight, which include the ailerons, the elevator and the rudder. The primary flight surfaces control the three main axes of the aircraft's orientation which are yaw, pitch and roll. The rudder, elevator and ailerons control these respectively. Secondary flight control system improves the performance characteristics of an aircraft or relieves the pilot of using excessive control force, namely the landing gear, flaps and trim systems. A validation of PBW actuation system on a primary flight control surface of a tactical aircraft has been done by replacing the standard hydraulic system with Electrically Powered Actuation Design (EPAD) system that were installed on the left aileron of the F/A-18B system aircraft (Jensen *et al.* 2000).

The PBW actuation system is of three types; Electro Mechanical Actuation, Electro Hydrostatic Actuation and Integrated Actuator Package (IAP). Electro Mechanical Actuator (EMA) uses a ball screw gear and mechanical linkage to couple an electric motor to a flight control surface. They provide a good modular design, ease of control, no leakage since fluid is not used for power transmission. But they add a backlash due to the

use of ball screw and failure of which leads to jamming of the actuator because of solid contaminants. In contrast to EMA, EHA uses hydraulic fluid for the power transmission to the flight surface. It is totally self-contained within the actuator assembly. Hydrostatic actuation system has a closed cycle architecture in which the return flow from the actuator goes directly back to the inlet of the pump. This closed cycle architecture allows it to be developed into a PBW actuation system. IAP is an alternative implementation of the EHA design principle which differs in the type of motor and pump used. In contrast to EHA, IAP uses a unidirectional fixed speed electric motor to drive a variable displacement pump that controls fluid flow to the actuator. With the pump rotating at constant speed, a separate control mechanism varies the swash plate angle within the pump, and is therefore able to continuously vary the fluid flow to the actuator. When the swash plate passes through the over-centre position, fluid flow is reversed, thus changing actuator direction. Navarro (1997) has described an EHA configuration testing methodology to demonstrate the applicability of PBW technology on a primary flight control system. The three types of actuation systems – centralised hydraulic system, EHA and EMA have been described and the advantages in choosing EHA are elaborated by Vladimirov and Forde (2006).

This paper gives a review of the works published by various researchers in the field of EHA system. Section 2 elaborates about the working of EHA system. Section 3 includes advantages and disadvantages of EHA system over the conventional hydraulic system. Section 4 deals with the several configurations of EHA and highlights on the recent developments of pump-motor packages of EHA system. Section 5 discusses the various components of EHA and the developments in their fields. Section 6 explores the various control strategies available for EHA system. Section 7 discusses the need and the approach for multidisciplinary modelling and simulation of the EHA system. Section 8 deals with the reliability and fault

tolerance capability of the EHA system. The thermal aspects of the EHA system has been discussed in Section 9 and various approaches for design optimisation have been elaborated in Section 10. Some of the published applications of the EHA have been briefly described in Section 11. The paper concludes in Section 12 with a summary of the current state-of-the-art on EHA system and a discussion on the areas for further research work.

2. Electro hydrostatic actuator

EHA is a PBW technology that replaces a traditional centralised hydraulic actuation system, by modular subsystems. Instead of using a centralised hydraulic circuit and power lines through the aircraft, modular hydraulic actuators with electric signal wires are used. The EHA is a self-contained hydraulic system consisting of a Brushless DC (BLDC) motor, bi-directional pump, accumulator, control elements, hydraulic actuator and controller built on a central manifold. The block diagram of a typical EHA is shown in Figure 1. The controller sends the electric control signal to the servo motor according to the input instruction and the servo motor takes this electrical signal and gives the corresponding rotational direction and speed to the pump, which in turn sends the hydraulic flow to the piston end and makes a pressure difference on both sides of the piston. The piston, which is driven by this pressure difference, makes the piston rod to move out. The sensor on the piston rod sends the information of displacement back to the controller. As the piston moves, it has to sustain elastic force, friction force, damping force and load force. The control elements include the Non Return Valves (NRV), Pressure Relief Valves (PRV) and the bypass valve. The NRVs are used as anti-cavitation valves and the PRVs are used to limit the system pressure. In case of any failure, the bypass valve will be activated, which cuts off the pump-actuator circuit and the flow from one chamber to other takes place through the bypass valve orifice till

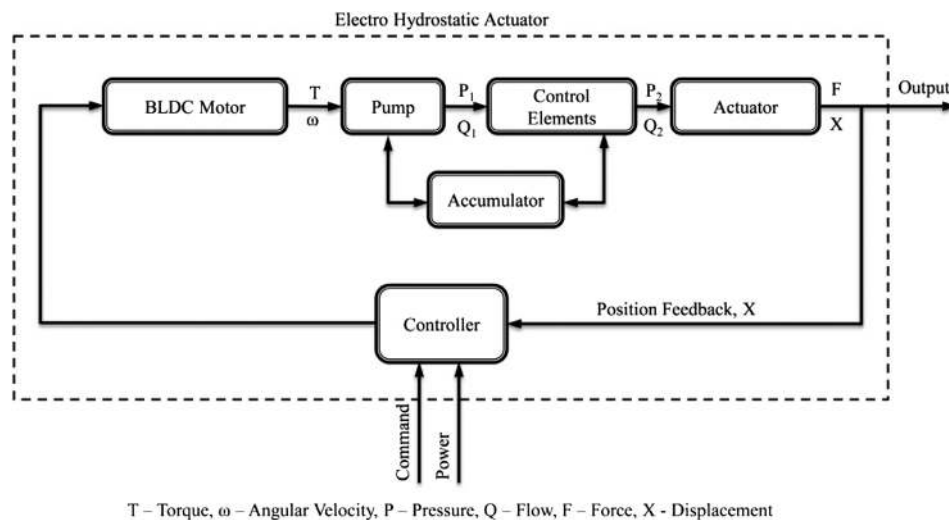


Figure 1. Block diagram of EHA system.

the actuator attains a balanced (equilibrium) condition and stops. The accumulator can be used as a hydraulic secondary source which enables the reinjection of the fluid corresponding to the pump leakage in the hydraulic circuit and also used when there is an insufficient inline pressure in the flow line to avoid cavitation. Bossche (2006) has discussed the performance achieved for an Airbus A380 flight control EHA and highlighted some lessons learnt. The A380 is the first commercial plane that offers to the operators and passengers the performance and weight benefits associated to the reduced number of centralised hydraulic systems, together with the added margin of safety provided by more reliable and dissimilar flight control actuation system. For many years there has been an understanding that EHA is simple replacement to centralised power pack system. Till recently, understanding the additional advantages by optimising the system configuration have been a challenge. The requirement is of course, to advance from simple system to energy optimised systems. The effects of flight control in both dynamic and energy consumption by substituting the conventional hydraulic actuator with EHA has been discussed by Hu *et al.* (2014).

3. Advantages and limitations of EHA

The EHA is a superior system when compared to the conventional, centralised hydraulic system. Nevertheless, it has some drawbacks too. The advantages and limitations of EHA in comparison with the conventional hydraulic system are detailed below.

3.1. Advantages

The conventional hydraulic system uses a centralised power pack in flight and uses a large amount of pipe lines and joints, which leads to severe leakage and pressure drop problems. The EHA on the other hand, draws electrical power from an on-board source and converts the low power electrical input command into motion. It improves the reliability of the system by eliminating the central hydraulic power supply and replacing the hydraulic pipe lines by electric power cables thereby simplifying the aircraft layout. EHA's also have lower weight compared to the bulky conventional hydraulic systems since they reduce the cumbersome internal routing of piping which further leads to a minimised fluid contamination and lesser leakage concerns.

EHA offer a high degree of combat survivability of aircraft flight control systems because of all the components necessary to operate the actuator are collocated with the actuator (Kang *et al.* 1995).

Centralised hydraulic systems are also not very economical to operate because of their higher maintenance costs and amount of time required to replace faulty items. This results in longer downtime for the aircraft. A single compact self-contained hydraulic servo actuator

system is easier to handle and replace in case of a fault as only electrical and signal cables need to be reconnected. This improves the maintainability of the flight control systems.

EHA consumes less power than conventional hydraulic actuation systems. Unlike the centralised system where the hydraulic pump runs continuously, the EHA draws electrical power from the common electrical power source only when the actuator is in working condition. When the motor stops operating, the internal pressure holds the actuator stationary (Habibi 2000). The EHA systems do not have the loss due to throttling and hence have higher efficiency.

3.2. Limitations

In spite of its several advantages, the EHA system suffers from some major drawback. When the conventional central hydraulic power supply is replaced by EHA, the frequency width and stiffness is decreased. To overcome the drawback, Rongjie *et al.* (2009) proposed a novel structure of EHA associated with a power regulator. The response is decided by the characteristics of motor or pump which may not satisfy the requirement of system response. EHA is more susceptible to cross-coupling effects in a multivariable system (Habibi 2000).

4. Different configurations of EHA

There are several working configurations of the EHA system that are available. Some of the EHA can be with fixed displacement Pump and Variable Motor speed or with Variable displacement Pump and Fixed Motor speed or with Variable displacement pump and Variable Motor speed. Fu *et al.* (2011) in their work on control strategies for EHA have highlighted the relative merits of the different configurations. The three different configurations and the research work addressed using these configurations are elaborated in the following sub sections.

4.1. Fixed pump and variable motor

Figure 2 shows a fixed pump and variable motor (FPVM) configuration of EHA. It consists of a fixed displacement pump and a variable speed motor. The bi-directional pump rotates at variable speeds driven by an electrical motor. FPVM-EHA has found applications in many aircrafts but there are still some problems like the frequency band width and stiffness that need proper solutions. Rongjie *et al.* (2009) presented a FPVM-EHA associated with a power regulator that improved the system performances through optimisation of the supplied power. The FPVM configuration of EHA is considered to have a simpler structure and higher efficiency than EHA-VPFM. Bellad (2014) developed a modular FPVM-EHA and a fuzzy PD controller for position tracking of the actuator.

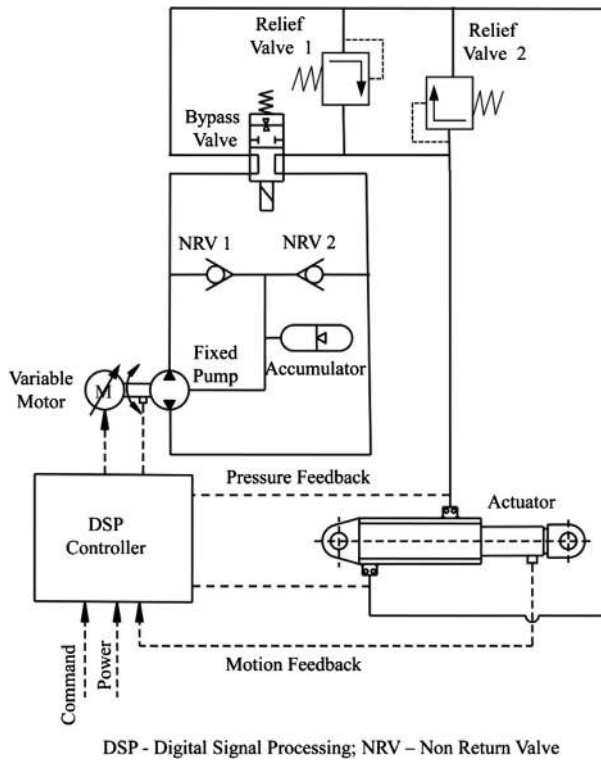


Figure 2. Fixed pump variable motor (FPVM) EHA (Kang, Jiao *et al.* 2008).

4.2. Variable pump and fixed motor

Figure 3 shows a Variable pump and fixed motor (VPFM) configuration of EHA. Here the motor speed is fixed and the pump displacement is varied by a servo motor. The swash plate angle of the axial piston pump is changed using the servo motor. The EHA-VPFM has faster dynamic response than EHA-FPVM, but the efficiency is comparatively low.

4.3. Variable pump and variable motor

Figure 4 shows a Variable pump and variable motor (VPVM) configuration of EHA. It consists of a bi-directional variable displacement pump and two servo motors that adjust the rotational speed of pump and the displacement of pump respectively. In this system, an electrically driven variable displacement servo axial piston pump is used as the bi-directional variable pump. The displacement of the pump can be adjusted by changing the angle of swash plate through one servo motor. The rotational speed of pump is adjusted by the other servo motor. As discussed by Zhang *et al.* (2010) the structure of EHA-VPVM consists of a hydraulic system with re-feeding circuit, bypass valve, relief valves and symmetrical actuator. The re-feeding circuit includes accumulator and check valves, is used to compensate for the leakage of hydraulic system, and supply oil when high flow rate is required in a short time. A low pressure gas charged accumulator re-feeds the two hydraulic lines through check valves in order to maintain a minimum

pressure inside. The bypass valve cuts off the hydraulic circuit to make the actuator work in damping bypass mode when failure of system occurs. The relief valves can limit the maximum pressure of the hydraulic system. In EHA-VPVM mode, the displacement and rotating speed of pump can be adjusted simultaneously, therefore, it can combine the advantages of the other two types of EHA.

5. Subsystems of EHA

Hydraulic pump, motor and actuator are the main sub systems of EHA. The motor controls the speed and direction of rotation of the hydraulic pump and hence controls the forward and backward motion of the actuator.

5.1. Hydraulic pump

Hydraulic pump in the EHA is used to convert the mechanical energy received from the electric motor into hydrostatic pressure and flow. Different types of pumps are used in different configurations of EHA like the external gear pumps, internal gear pumps, axial piston pumps and vane pumps. Gear pumps are essentially of the fixed displacement type, axial piston pumps and vane pumps can be either of the fixed displacement type or of the variable displacement type. McCullough (2011) discussed two main forms of hydrostatic actuation systems – one which uses a variable-displacement piston pump and another that uses a fixed-displacement external gear pump.

Gear pumps are suitable for high temperature applications because of their simple structure, low cost, and higher reliability (Xu *et al.* 2010). They have redesigned a gear pump to suit high temperature environment of about 403 K. The gear and its house were made of the same material and all seals and the bearings in the pump were improved to withstand at high temperatures. High speed rotation of the gear pump makes it particularly suitable for EHA (Gendrin and Dessaint 2012). The meshing topology provides the lubrication but also leads to backlash effect. According to Ivantysyn and Ivantysynova (2003), the internal gear pumps can achieve distinctly lower non-uniformity grade of the flow rate. Manring and Kasaragadda (2003) concluded that it is advantageous to design an external gear pump with a large number of teeth on the driving gear and a fewer number of teeth on the driven gear as it tends to reduce both the physical pump size without reducing the volumetric displacement of the pump and the amplitude of the flow pulsation, while increasing the natural harmonic frequencies of the machine. These points can be used while designing an external gear pump for an EHA in flight control actuation system where size and volumetric displacement are of utmost importance.

Variable vane pumps use a series of extending and retracting vanes whose position is dependent on the rotary orientation of the central lobe to which they

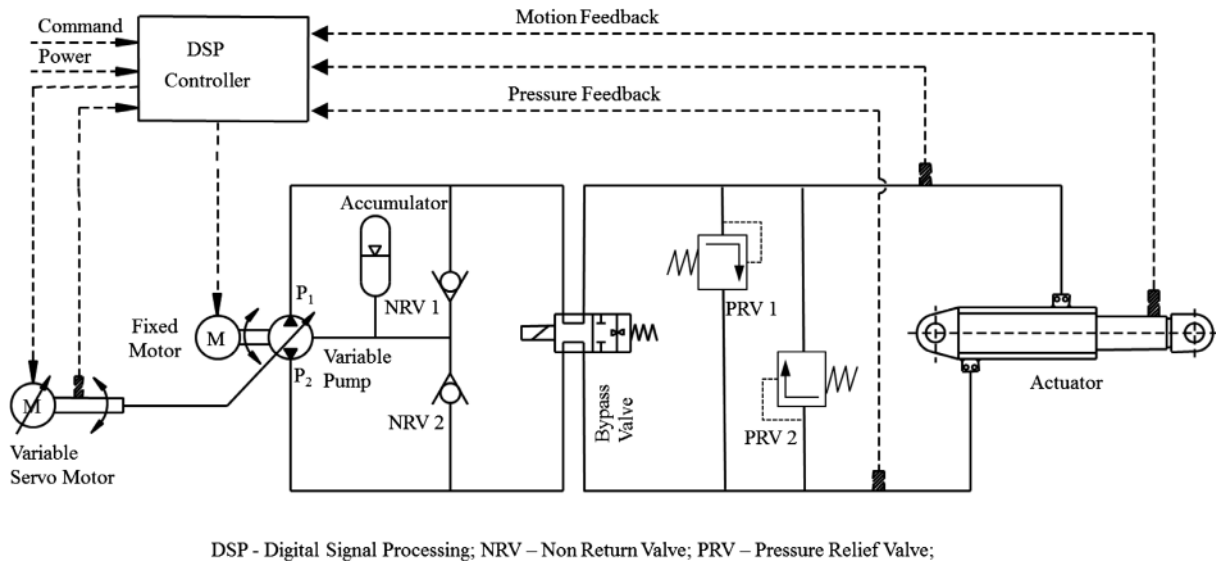


Figure 3. Variable pump fixed motor (VPFM) EHA.

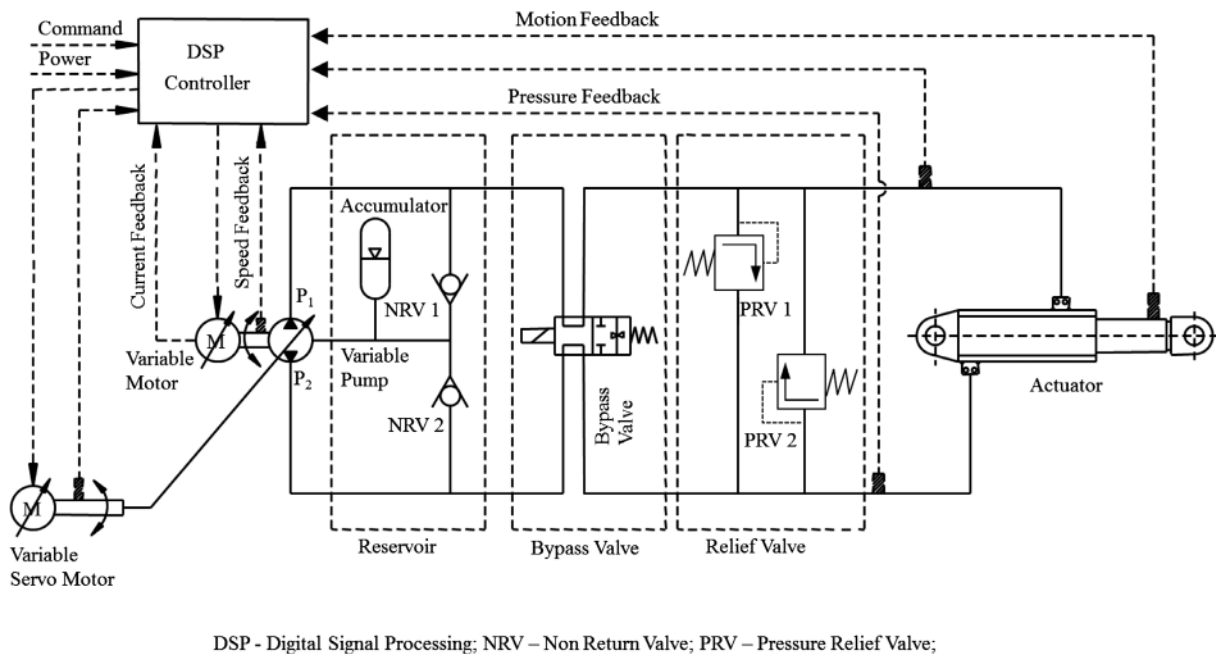


Figure 4. Variable pump variable motor (VPVM) EHA (Zhang *et al.* 2010).

are attached to. To vary the volumetric displacement, the lobe is shifted in its chamber back and forth to alter the volume of fluid that the vanes can displace. Although simple and compact, variable vane pumps are not employed in hydrostatic circuits for flight surface actuators since they require a speed of at least 52.4 rad/s (500 rpm) and they cannot displace enough fluid at a higher pressure (Eaton Hydraulic Training Services 2006).

Axial piston pumps can be either fixed displacement type or variable displacement type. A typical bidirectional axial piston pump contains three ports, two reversible input/output and one smaller port that collects the leakage flow. Flow from a fixed displacement, axial piston pump can be controlled by varying the speed of

the electric motor. Variable displacement in axial piston pumps is achieved through swash plate arrangement driven electrically by a secondary high response electric motor. Anderson (1991) has listed down the advantages of using variable displacement pump in EHA like reduced package heating, higher actuator stiffness and lower package size. A detailed explanation of how these parameters are advantageous when a variable displacement pump is used in EHA is given in Anderson's paper. Bo *et al.* (2005) described an electrically driven variable displacement, bidirectional axial piston pump where the swash plate is driven by servomotor and segment gear arrangement instead of servo valve and the cylinder. In such type of arrangement, the back drivability of the actuator can be prevented by reducing the swash

plate angle to zero when required. Hence due to above advantages and because of the higher response; variable displacement, bidirectional axial piston pump are ideal for flight control applications. Their only disadvantage is their added complexity.

5.2. Electric motor

Electric motor drives the hydraulic pump of the EHA and is one of its most critical components from the point of view of actuator control. Following are some of the recent developments in the field of electric motors that have made the realisation of PBW systems like the EHA a reality.

Flight control application requires a compact motor with high power density and acceleration capacity. The use of high energy density rare earth permanent magnets to replace electromagnetic poles of motor and the development of electronic commutation circuits for electric motors have helped in the development of high performance brushless motors for aerospace applications. These motors are without the brushes, slip rings or mechanical commutator that are present in conventional DC motors or synchronous AC motors. Here the armature of the motor is placed on the stator. This solves the brush-linked problems such as Electro Magnetic Interference and its associated sparking. The absence of commutator reduces the motor length. Hence, the lateral stiffness of the rotor is greater, permitting higher speed required for servo applications. Conduction of heat through the motor frame is improved. Hence increase in electric loading is possible and may provide a higher specific torque and higher efficiency. These type of electric motors are now widely used for flight control and are classified on the basis of the wave shape of their induced electro motive force (e.m.f.), i.e. sinusoidal and trapezoidal. The sinusoidal type is known as Permanent Magnet Synchronous Motor (PMSM) or Permanent Magnet Brushless AC Motor and the trapezoidal type is called as permanent magnet Brushless DC (BLDC) Motor. The choice of the type of motor would depend on the type of power supply on board the system, e.g. if an available AC power supply on an aircraft were to directly drive the motor, PMSM will be used.

From the literature it has been noted that the overwhelming use of the BLDC motor in the EHA system enhances the performance. The only major disadvantage of the BLDC motors is the need for shaft position sensing (Elbuluk and Kankam 1995a). Jahns and Van Nocker (1989, 1990) have suggested an alternate permanent magnet configuration for the use in BLDC motors called the Internal Permanent Magnet (IPM) in the place of the commonly used Surface Permanent Magnet (SPM) configuration. In SPM motors, the non-magnetic sleeve covers the rare earth magnets that are mounted on the rotor whereas in IPM motors, the rotor magnets are placed inside the iron core. The new configuration

is mechanically and electrically more robust and when coupled with efficient controller electronics can provide high efficiency and fast dynamic response over a wide operating speed range with low electrical losses. High performance BLDC servomotors are powered and controlled by a Pulse Width Modulation-Vector Source Inverter (PWM-VSI) and Insulated Gate Bipolar Transistor (IGBT) inverter stage. This has allowed BLDC motors to attain fast response of torque control and low torque ripple (Matsuse *et al.* 2013). Wheeler *et al.* (2004) recommended the use of matrix convertor permanent magnet motor drive for EHA that are used in aerospace applications due to advantages in size, weight and the absence of the requirement for electrolytic capacitors. The latest research is now towards adopting silicon carbide and gallium nitride as materials for power semiconductor devices in motor drives. For the EHAs to be used in critical flight control applications, the BLDC motor would require a reliable control algorithm which would ensure safe start-up and operation. Hubik *et al.* (2008) dealt with the analysis and simulation of the start-up phase of the BLDC motor. They have discussed the development of control algorithms and electronics to improve run up performance of the BLDC motor in EHA for safety critical applications that would allow closed loop control much sooner in the start-up phase than was previously possible.

5.3. Hydraulic actuator

Hydraulic actuator is the working element of an EHA system, used to convert hydraulic pressure and flow into force and velocity of the actuator. In aircraft, EHA is used to transfer linear motion and power to the linkages of control surfaces or engines. Two types of actuator designs are being used in EHA system - asymmetric design (single rod) and symmetric design (double rod). EHA with symmetric actuators are generally used in flight control actuation systems whereas asymmetric actuators are preferred for industrial applications.

A symmetrical actuator specifically designed for the EHA system is reported by Habibi and Goldenberg (2000). This has the following advantages over asymmetric actuator as:

- Volume of hydraulic fluid displaced by the two primary chambers of the actuator are equal,
- Equal maximum saturation speed and torque,
- Dynamic characteristic is the same, thus simplifying the controller structure.

The use of a double-rod symmetrical cylinder keeps the inflow of the pump equal to the outflow during the motion of the load as the aerodynamic load is approximately symmetrical around zero (Gendrin and Dessaint 2012). Flow balance between the actuator and the pump is ensured using a symmetrical actuator in the EHA.

Oh *et al.* (2012) investigated the characteristics of the single-rod cylinder using mathematical models along with other subsystems of EHA hydraulic circuit and an electric motor. The performance of a closed-loop hydraulic control system incorporating the EHA with load and controller has been studied. Takahashi *et al.* (2008) presented the concept, in which hydraulic reservoir is built inside the piston rod of the EHA instead of having a full-volume reservoir outside its cylinder. This type of arrangement leads to volume and weight reduction.

6. Control methods

Nonlinear problems in flight control have always remained a field of study for scientists all over the world. The EHA system presents to the control engineer not only the nonlinearities but also some issue like the dead band which is peculiar to the EHA system.

The following sections list some of the challenges in EHA system for flight control and describe how the researchers have tackled the problems.

6.1. Nonlinearities in EHA

The dynamic characteristics of EHA system are complex and nonlinear. The nonlinearities arise from the friction in the hydraulic actuator and the compressibility of the hydraulic fluid. The variation in efficiency of the pump (due to change in direction, pressure operating point and its speed of rotation) and the volume variation caused by the movement of the piston make the EHA characteristics complex (Perron *et al.* 2005). Things become even more complex when the EHA-VPVM configuration of the EHA is used which is a Dual Input Single Output nonlinear system with multiplicative nonlinear property. Hence the fixed gain control laws cannot be used for controller design of the EHA system. Zhang *et al.* (2010) and Zhang and Li (2011) linearised the EHA system through feedback linearisation and designed the position control system using optimal control theory. They have been able to meet the different requirements on dynamic response by adjusting the weighting coefficients of the displacement and the rotational speed of pump.

6.2. Dead band

The effects of friction in the EHA system are not only nonlinear but also discontinuous. Even the use of a nonlinear gain Scheduled Proportional Controller (SPC), as proposed by Sampson *et al.* (2004) results in oscillations in the system response for small input signals at cross over regions where the velocity changes its sign (Wang *et al.* 2008). This effect is known as the dead zone and is unique to modular actuation systems like EHA and EMA and affects

the stability, manoeuvrability and the flight profiles of aerospace systems (Habibi *et al.* 2008). In EHA dead band occurs mainly due to static friction in the motor, pump cross-port leakage coefficient and the pressure drop across the actuator/pump connection (Habibi and Goldenberg 2000, Jun *et al.* 2004b). Park *et al.* (2009) used a modified Proportional Integral Derivative (PID) controller using Inverse Sinusoidal Input Describing Function (ISIDF) to mitigate the effects of the dead zone. Many researchers (Jun *et al.* 2004a, 2004b, Liviu *et al.* 2010) used a dead zone pre-compensator to eliminate the control voltage dead zone whereas a load pressure positive compensator used to handle the effect of load torque on the angular velocity of the motor.

EHA can be desensitized to the effects of the dead zone by using the control strategy with the multiple inner loops consisting of a high-gain inner-loop velocity control of the driving motor and the inner-loop compensation for the differential velocity between the motor vs. the control surface (Habibi *et al.* 2008). A cascade controller has three loops namely – motor current loop, motor and pump speed loop and the hydraulic actuator linear position loop. Position controller assigns the control voltage of Pulse Width Modulation (PWM) drivers of the motor. The velocity feedback forces the motor and pump to track the angular velocity given by command input. The current in the coils of the motor are adjusted and limited by the current feedback control (Jun *et al.* 2004a). Kang, Mare *et al.* (2008) concluded that the cascade PID control efficiently helps the system to meet the EHA requirements of rapidity and stiffness but may lead to some oscillations. Hence they used the state feedback control along with dynamic pressure feedback strategy for improving both static and dynamic performance of EHA. Jun *et al.* (2004b) have used the multi-loop cascade PID control and have taken care of the nonlinearities using the Fuzzy Logic Controller (FLC) that tunes the PID coefficients automatically.

6.3. Sensor noise

In the above control methods, the motor's angular rate, current and piston's position are measured using sensors like Hall Effect sensors and Linear Variable Differential Transformer (LVDT). All these sensors introduce some degree of inaccuracy. High system gain tends to amplify the effects of sensor noise (Kang *et al.* 1995). An effective counter measure to sensor noise is to decrease the control system's loop gain as much as possible, while still meeting specifications, e.g. tracking and disturbance rejection. Multiple Input Single Output-Quantitative Feedback Theory (MISO-QFT) allows for such a balance economically (Kang *et al.* 1995). It is used to achieve a robust control design and is preferred to standard high gain design for sensor noise rejection and bias handling characteristics. Kang *et al.* (1995) used QFT method to

design a controller for EHA, which is not only insensitive to sensor noise but also robust with respect to actuator parameter variations and flight conditions.

6.4. Parameter uncertainties

Wang *et al.* (2008) conceived a Sliding Mode Control (SMC), which is preferred for its robustness to parameter uncertainties, external disturbances and un-modelled dynamics. But performance of SMC can be severely degraded by noise. Hence, Wang, Burton *et al.* (2011) proposed a method referred to as the Sliding Mode Controller and Filter (SMCF) that uses robust state and parameter estimation strategy called the Variable Structure Filter (VSF) in conjunction with SMC. Both SMC and the VSF have inherent switching actions that can lead to chattering. This problem has been addressed in the SMCF through the introduction of a boundary layer and a bypass high-frequency loop that is formed by SMC and VSF.

Robust controllers can guarantee a control only when the parameters and conditions vary within a certain bound. Adaptive control on the other hand does not need prior information about the bounds of uncertain or time varying parameters. Simple Adaptive Control (SAC) is a control methodology based on a two-degree-of-freedom control system. Cho and Burton (2011) have shown that there is a significant reduction in position tracking error under external disturbance load when SAC is used in an EHA when compared to conventional PID control. Back stepping is a powerful, nonlinear control strategy due to its ability to ensure an asymptotic stability of the controlled system without cancelling useful nonlinearities (Kaddissi *et al.* 2011). Seo *et al.* (2010) used an Adaptive Back-Stepping (ABS) controller with reconstruction error estimator to guarantee stability for unknown parameters and a Radial Basis Function Neural Networks (RBFNN) algorithm to estimate system uncertainties. Kim *et al.* (2010) explained the use of ABS control scheme with Fuzzy Neural Networks (FNN) for EHA. Direct Adaptive Controller (DAC) uses estimated parameters directly. On the other hand Indirect Adaptive Controller (IAC) uses controller parameters that are calculated from the estimated parameters. When the identification algorithm is limited to the gradient type, the DAC cannot separate the control law design from the parameters estimation law. Therefore, the estimated parameters are not accurate enough to be used for predictions. According to Kaddissi *et al.* (2011) IAC guarantees the convergence of the system parameters to their real physical values as well as ensures the system stability. They used an indirect adaptive back stepping approach for the position control of EHA with the aim of identifying and tracking the variation of the system parameters with the operating conditions. Ahn *et al.*

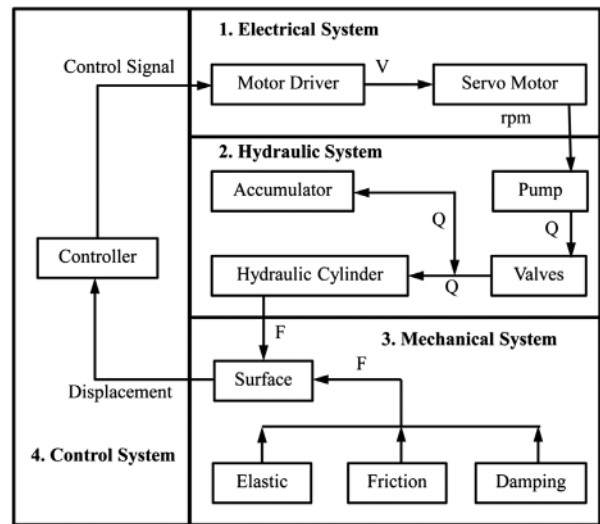


Figure 5. Subsystems of EHA system (Li and Wang 2010).

(2014) have presented an adaptive position control for a pump controlled EHA based on an adaptive back stepping scheme. The main feature is the combination of a modified back stepping algorithm with a special adaptation law to compensate all nonlinearities and uncertainties in EHA system.

The two important aspects that determine the success of the EHA controller are the accuracy of the mathematical model and the effectiveness of the control strategy. Fuzzy controllers are chosen for nonlinear systems because they decrease the effects of inaccuracies in mathematical model and have more simple interpretation than other controllers.

7. Multidisciplinary modelling approach and simulation strategies

The mathematical model of the EHA is required in order to design a good controller based on conventional control strategies like Proportional Integral Derivative (PID) control, robust control, state space control, etc. This is not an easy task as EHA is an integrated system dealing with many different kinds of disciplines like electronics, hydraulics and mechanics and one must have a good knowledge about each of these disciplines. Moreover the mathematical model of the EHA is necessary for simulation studies of the dynamic characteristics. So the different multidisciplinary modelling methods used in designing an EHA system irrespective of their application are elaborated below.

7.1. Need for multidisciplinary approach

The main components of EHA system can be divided into four subsystems according to their characteristics *viz.* electrical subsystem, hydraulic subsystem, mechanical subsystem, control subsystem and are related as shown in Figure 5 (Li and Wang 2010). The electrical

subsystem consists of the motor driver and servo motor to drive the pump. The hydraulic subsystem consists of the pump, accumulator, control elements like valves and hydraulic cylinder. The control subsystem consists of a controller. EHA being a closed circuit system, the heat generated during operation cannot be removed by the circulating oil to the reservoir (heat sink) and so the heat is also considered as one of the disciplines of EHA. When modelling a multidisciplinary model, it is important not to neglect the multidisciplinary coupling characteristics which may cause low efficiency or even failure. There are two approaches to modelling of EHA. One approach is to use conventional modelling approach- mathematical method to obtain the transfer function which may not be always accurate due to use of simplifying assumptions and abstractions. Another approach is to build the multidisciplinary model by bond graph technique and solve using the commercial software tools like AMESim and 20-SIM.

7.2. Conventional modelling approach

The first method is the conventional transfer function based approach adopted by most of the authors like Habibi and Goldenberg (2000). The complexity of EHA makes the development of exact model a difficult task. Therefore simplified plant models are obtained by linearisation around the operating points (Rabbo and Tutunji 2007). This approach gives less than a realistic description of the EHA as they have neglected the nonlinearities in the system. The nonlinearities may arise due to the nonlinear effect of the re-feeding hydraulic circuit, the effects of frictional resistance to the translational and rotational elements of the system, the dead band associated with the pump motor unit and the control side-effects such as the noise produced from hysteresis regulation (Gendrin and Dessaint 2012). Hence Kang, Jiao *et al.* (2008) modelled a typical architecture of the EHA using the block diagram based on mathematical equation and have arrived at a more realistic nonlinear accuracy model of the EHA.

7.3. Bond graph modelling approach

Bond graph methodology is based on the concept of power transmitted or energy exchange between system components by a combination of effort and flow. Transfer functions can easily be found out from a bond graph design (Langlois *et al.* 2004). Therefore bond graph is helpful in efficiently modelling multi-field and heterogeneous systems such as EHA. Bond graph structure facilitates the study of parameter variations. This helps to size components and optimise a complete system (Langlois *et al.* 2004). Borutzky (2002) compared Object Oriented Modelling (OOM) and the bond graph methodology and concluded that bond graph modelling may be viewed as a form of OOM. Hence it is possible

to describe bond graph models in the multi-purpose object-oriented languages like Modelica. As an example, a controlled hydraulic drive has been modelled using the bond graph and described in the Modelica by Elbuluk and Kankam (1995b). Ould Bouamama *et al.* (2002) used bond graph as a tool for Fault Detection and Identification (FDI) design by using an external model that describes a system in terms of functions without taking into account its physical and dynamic behaviour. Langlois *et al.* (2004) modelled a complete EHA system from the electrical power supply to the flight control surface using bond graph and implemented in Saber software. The results of the simulation were compared with that of the behavioural model supplied to Airbus by the manufacturers and the results were found to match closely.

7.4. Collaborative simulation

Collaborative simulation or co-simulation is another method to design complex products with multidisciplinary characteristics. This methodology allows individual components to be simulated by different simulation tools that run simultaneously and exchange information between them. Li and Wang (2010) presented a modelling method for EHA based on the collaborative simulation using AMESim (multidisciplinary modelling) and MATLAB (mathematical modelling) to improve the model accuracy and realise the performance optimisation. The collaborative simulation has been implemented by the interface module which is built in AMESim and changed to a S-function which can be used in Matlab. Wang *et al.* (2009) applied multidisciplinary and collaborative optimisation during the structural design to optimise the reliability and control performance of the EHA. Multidisciplinary models are limited to two or three disciplines and do not reflect the multidisciplinary coupling characteristics of the whole system. Li and Wang (2011) analysed the integral disciplines of the EHA system and have built the analysis-model for every discipline. Then an integral multidisciplinary coupling model of the EHA system has been built through the analysis of the coupling relation between each analysis-model.

7.5. Model identification

Even a very detailed and well-built model will have limitations as the exact values of important parameters like coefficients for discharge, flow, leakage, friction and bulk modulus cannot be derived theoretically and has to be arrived at only experimentally. Hence before the model can be used in embedded controllers, the technique of model identification can be used to improve upon a model by using the experimental results. Habibi *et al.* (2000) used model identification technique to derive a range of values for unknown parameters like cylinder leakage coefficient and effective bulk modulus. They have

then validated the model through open-loop testing of the system. The derived model closely matched with the measured response at low to medium frequencies of excitation. Rabbo and Tutunji (2007) showed that the recursive identification models can be used for the identification and analysis of hydrostatic systems and have studied the effect of variation in volume displacement, the motor torque on pressure and hydraulic motor speed.

8. Reliability, redundancy and fault tolerance

Aerospace subsystems, especially those that are used on aircrafts have to be highly reliable and fault tolerant. EHA system is a complex system and any one of its several components can fail during operation. A reliable EHA system is one which fulfils its function without interruption for a specified period of time – EHA is operational when needed. In contrast to reliability, availability also depends on maintenance strategies.

8.1. Redundancy, reliability and availability

Redundancy is a prerequisite for fault-tolerant systems. Redundancy has to be ensured both at the flight control surface level and at the subsystem level – EHA system.

Physical redundancy at the flight control surface level would mean the use of multiple EHAs or a combination of EHA and EMA in parallel on a flight control surface. Failure of one unit can then be accommodated using a simple hydraulic by-pass valve in case of multiple EHAs. (Huang *et al.* 2006). But this would increase system cost and weight. To minimise the chances of actuators of the same surface getting affected at the same time, functions such as bypass, movement damping and load limiting have to be provided. If the actuators drive the surface simultaneously, load sensing and compensation means are useful to avoid design for force fight related overload (Frischemeier 1997). EHA systems are superior to EMA when physical redundancy is used. A failed EMA can jam the control surface/system and prevent operation of back up EMAs, whereas simple hydraulic valve allows the hydraulic ram of the failed EHA to move freely as the flight control surface moves under the control of the remaining healthy units (Huang *et al.* 2006). Redundancy at the subsystem level, i.e. within the EHA, can be realised either through physical redundancy or analytical redundancy.

Physical Redundancy would refer to the duplication of critical sensors on the EHA. It would allow the use of simple schemes for the detection and alleviation of faults and failures but would increase the overall cost of the system.

Analytical Redundancy on the other hand refers to the functional relationship between system inputs and outputs, rather than to the components themselves. Though more challenging, it would help in reducing the cost of the EHA. Model matching and fault hiding are two approaches for analytical redundancy that use

automatic design – reconfigurable or active fault tolerant control (FTC) as shown in Figure 6 (Lunze and Richter 2008). A model-matching approach aims at finding a controller that assigns the reconfigurable closed-loop system, which follows the same behaviour as the nominal closed-loop system (Lunze and Richter 2008).

For reliable and safer EHA systems FTC or reliable control can be used considering the expected failures at its design stage. A reliable control EHA system is more maintainable than conventional hydraulic systems and hence more available.

8.2. Fault tolerant control

FTC can either be of the active type or of passive type.

An Active FTC system reacts to component failures by reconfiguring control actions and relies on FDI scheme, for up-to-date information about system status. It allows the feedback control to remain operational after severe faults and failures. As shown in Figure 7 (Lunze and Richter 2008) active or reconfigurable FTC augments the ordinary control loop (execution level) by a supervision level with the aim to satisfy the loop performance requirements for both the faultless plant and the faulty plant (Richardeau *et al.* 2007). Model based control, quantitative reasoning and neural networks are employed for active FTC.

A Passive FTC system, on the other hand, can tolerate component failure by maintaining stability and performance by means of robust control, by reliable H_∞ design or by simultaneous stabilization. Once operational, the closed-loop system need not be changed to respond to a fault. But the set of faults that can be tolerated without active controller re-adjustment is severely limited (Lunze and Richter 2008). However passive FTC schemes can be derived in a straight forward manner when compared to active FTC schemes as it mostly uses single fixed-gain control law without depending on fault diagnostic algorithms. A fixed-gain linear time-invariant passive fault tolerant controller synthesised via Quantitative Feedback Theory (QFT) has been used successfully to maintain tracking performance against malfunctioning position sensors and hydraulic pump (Niksefat and Sepehri 2002) and leakage due to faulty actuator piston seal (Karpenko and Sepehri 2003, 2005).

8.3. Fault detection and identification

FDI plays an important role in reconfigurable active FTC. They are classified as signal-based fault detection methods and model-based fault detection methods. Both the methods depend on sensors. The sensors can provide signals for the position of actuator, the pressure of hydraulic system, the angle of swash plate, the current and the rotational speed of the servo motors (Zhang *et al.* 2010). Figure 8 shows typical sensors in an EHA configuration.

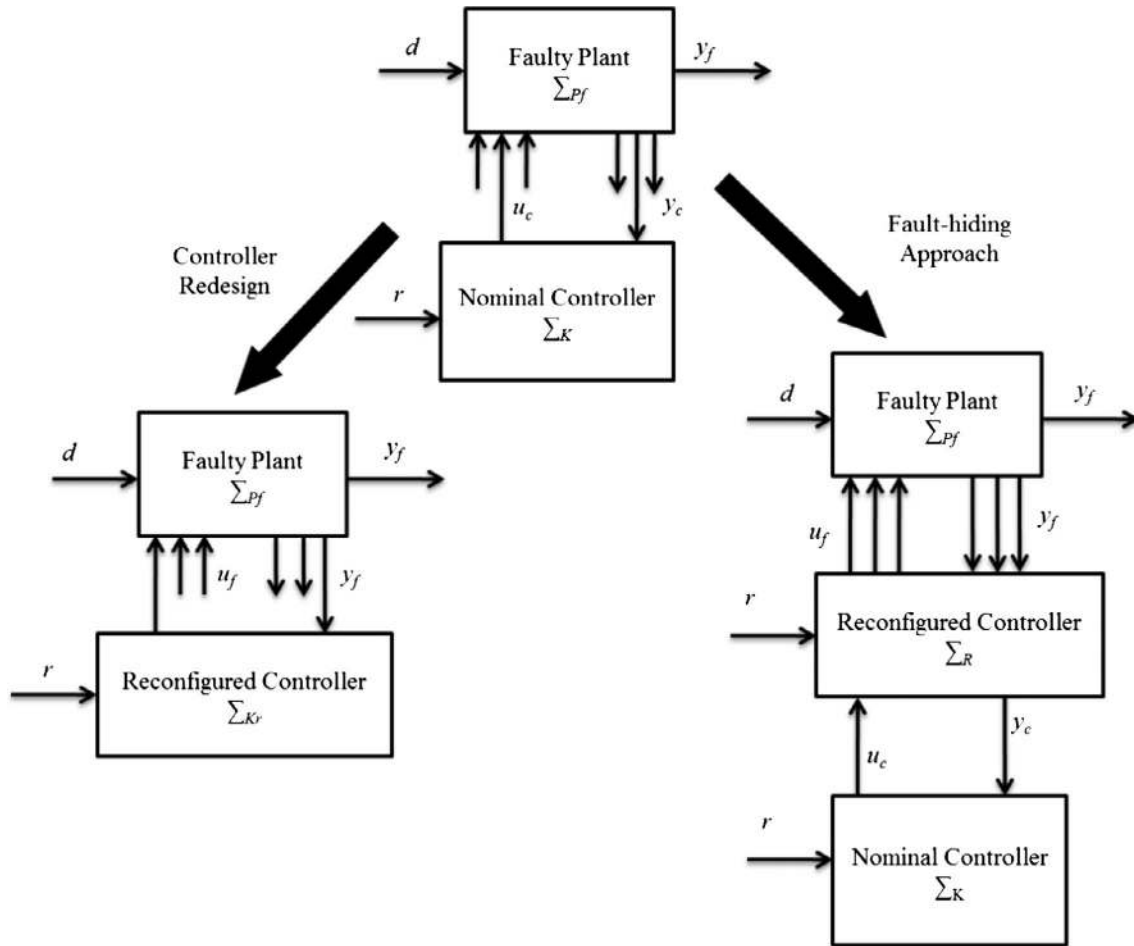
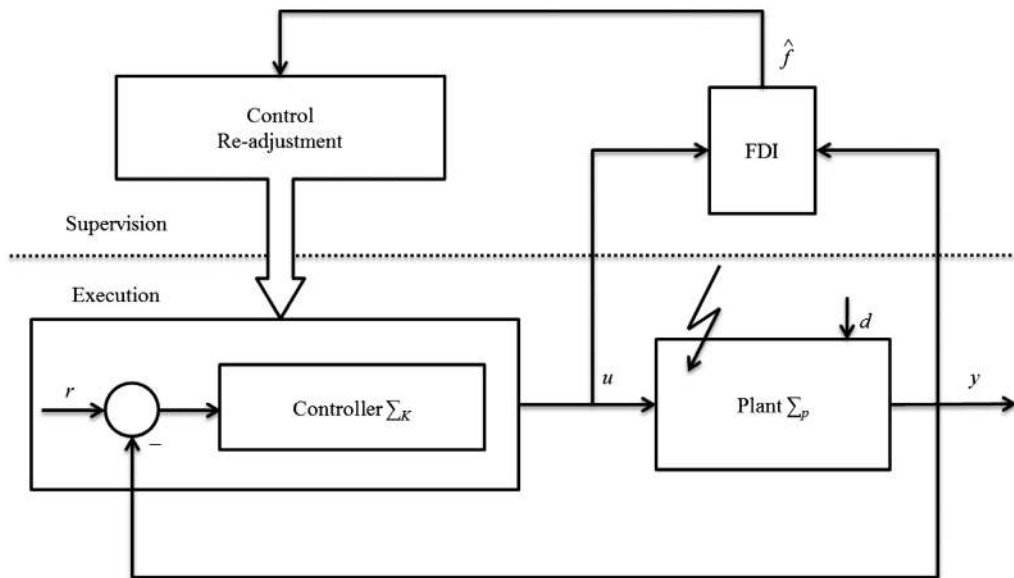


Figure 6. Approaches for active FTC (Lunze and Richter 2008).

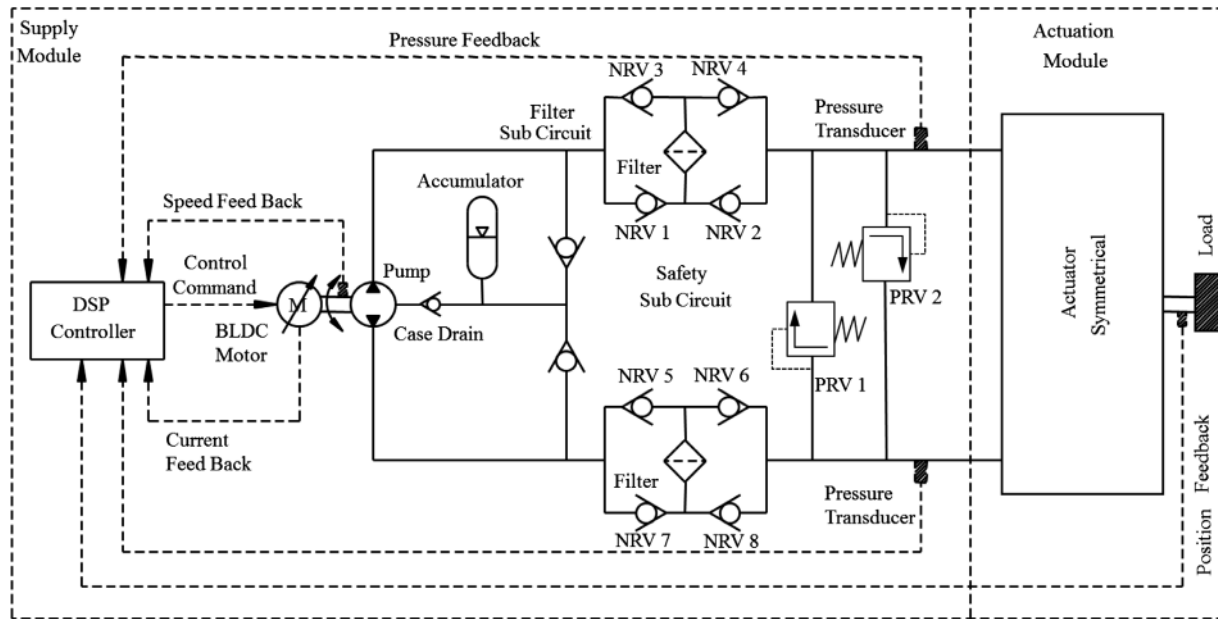


r – Reference Input; u – Input; y – Output; Σ_K – Controller Model;
 Σ_p – Plant Model; d – disturbance; \hat{f} – Fault Estimate; FDI – Fault Detection and Isolation

Figure 7. Active or reconfigurable FTC (Lunze and Richter 2008).

Signal-based fault detection methods use thresholds to extract information from available measurements and use it to determine if a fault is present. Signal-model

based methods are preferred for fault detection of electric drives and hydraulic pumps. Rotor defects can be detected by an analysis of the stator current. The



DSP - Digital Signal Processing; NRV – Non Return Valve; PRV – Pressure Relief Valve; BLDC - BrushLess Direct Current

Figure 8. Sensors/transducers in EHA (Habibi *et al.* 2000).

comparison of a torque-model based on the stator voltages and a second model based on the rotor-currents can help in detecting faults (Muenchhof *et al.* 2009). A nonlinear observer based principle combined with Wald's sequential test has been proposed by Khan *et al.* (2005) to detect faults. The fault detection process is facilitated using the control signal and the actuator's linear velocity, which are the measurable input and output variables respectively. Observer based methods assume that more than one internal states of the system - differential chamber pressure can be measured and the effect of the external forces are known or can be neglected. Marton and Varga (2011) formulated a fault detection method for EHA system, where the rod position is the only measurable state of the actuator and the external load generated force is not measurable but its limits corresponding to normal operation are known.

Model-based fault detection methods, on the other hand, takes into account faults which can be modelled through system identification. This type of fault detection and diagnosis is used when well-defined models can be created and utilized (Gadsden *et al.* 2011). Model-based approaches use the Kalman Filter (KF) for estimation of parameters. But KF is applicable to linear systems only. Hence Extended Kalman Filter (EKF) which is an extension of KF for nonlinear problems can be used to identify physical quantities such as the laminar leakage coefficient, increased friction of the piston, etc. (Muenchhof *et al.* 2009). Chinniah *et al.* (2006) used EKF for estimating the viscous friction and effective bulk modulus to detect faults in EHA systems. EKF for identifying cross-port

internal leakage as well as cylinder chamber external leakage at either side of the actuator is detailed by An and Sepehri (2004). Gadsden *et al.* (2011) introduced a new type of Interacting Multiple Model (IMM) filtering method by combining the standard IMM with Smooth Variable Structure Filter (SVSF) as detailed by Habibi (2007) for the purpose of fault detection and diagnosis. Wang and Syrmos (2009) developed an EKF-based multiple-model estimation scheme to fuse the FDI results from IMM algorithm with the fault estimation using EKF method to generate more accurate fault diagnosis. It can be used not only to estimate the faulty state but also to extrapolate the trend of faulty state which can be used to avoid the catastrophic failure. Wavelet transform is an extended time-frequency analysis used to get wavelet coefficients at different scales. Wavelet transform has been shown to be more sensitive and robust than spectrum analysis in detecting faults associated with hydraulic pumps (Gao *et al.* 2005). Wavelet transform also be used for both offline and online internal leakage detection as detailed by Goharrizi, Sepehri and Wu (2009), Goharrizi and Sepehri (2010a, 2010b). Goharrizi *et al.* (2011) studied the external leakage fault detection and its isolation from internal leakage in hydraulic actuators. A new filtering strategy was proposed by combining a stationary wavelet transform with relatively new SVSF, that reduces the SVSF chattering effect and improve the overall estimation accuracy. The results of applying the KF, SVSF, Wavelet transform based KF and Wavelet transform based SVSF on an EHA were compared and discussed by Zhang *et al.* (2012).

8.4. Component reliability

In order to design a reliable EHA, reliability has to be built into each of the components and the sub-systems. A total fault-tolerance EHA system must have fault tolerant actuators and drives, fault tolerant sensors as well as fault tolerant controller.

The motor is one of the critical components of the EHA system. Bearing defects can be reduced and reliability can be increased by using wet motors, where hydraulic oil is present in the motor in order to reduce the number of oil seals as discussed by Huang *et al.* (2006) and Huang *et al.* (2011). In case of BLDC motors, fault detection methods can be combined to achieve optimal performance under various operating conditions as outlined by Muenchhof *et al.* (2009). In this paper, parameter estimation has been used to determine the flux linkage and the resistance of the armature windings whereas parity equations are used to calculate five residuals. Logic to monitor the signals from the three hall sensors for improper combinations of their outputs are also used to detect a fault. The detected faults include overheat, winding interruptions and increased friction. All sensors are monitored for offset and stuck-at faults.

The hydraulic cylinder is one of the actuation module of the EHA. As shown in Figure 9 (Muenchhof *et al.* 2009), a typical fault tolerant hydraulic cylinder of EHA consists of two opposite acting cylinder chambers that are connected to one fixed displacement pump each. Bypass valves allow the piston to move whenever the pump axle is blocked and the pump is not able to rotate (Muenchhof *et al.* 2009). But such an arrangement will increase the size and weight of the EHA. Moreover a double rod cylinder has to be designed to ensure equal active piston areas in all chambers.

8.5. Dynamic reliability

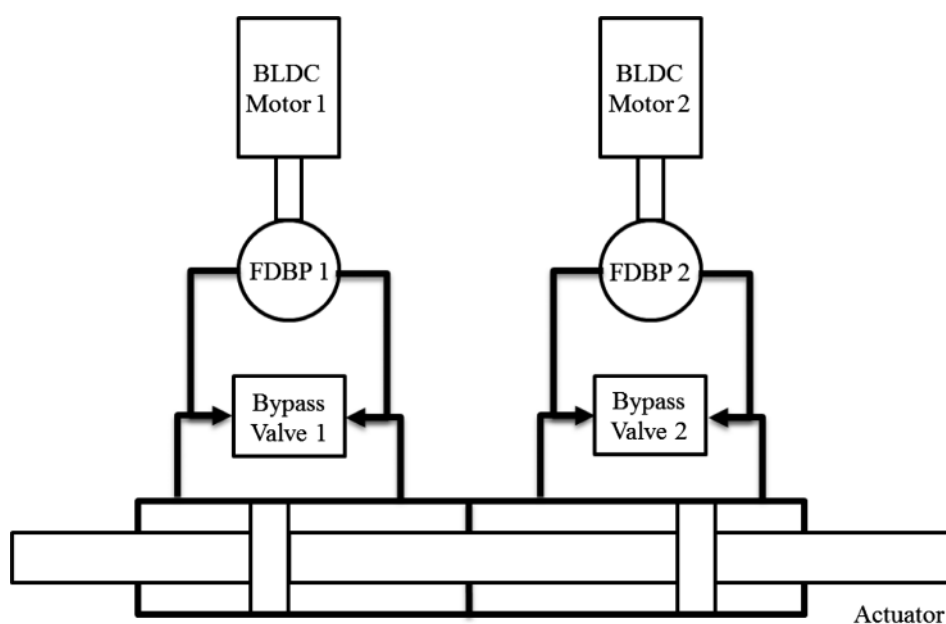
It is difficult to assess the dynamic reliability in the multi-state varying systems like EHA using traditional techniques like Monte Carlo simulation (Wang, Zeng *et al.* 2011). Hence, powerful mathematical frameworks have been developed that are capable of handling the interactions among the components and the process variables. They constitute a more realistic modelling of systems for the purpose of reliability, risk and safety analysis (Labeau *et al.* 2000). Wang, Zeng *et al.* (2011) proposed an integrated method of dynamic performance and reliability that uses Markov models, simulation and probabilistic dynamics.

9. Thermal effects

In the traditional hydraulic system, the heat generated in the hydraulic actuator is brought back to the reservoir by the hydraulic oil which gets cooled there. But heat can only be removed by local heat transfer in the EHA system. Removing the centralised hydraulic system eliminates an effective heat transfer network, thus resulting in less overall heat to reject but with localised 'hot spots' such as high-power motors and motor controllers. The following sub-sections look into the aspects of thermal analysis and thermal management taking into consideration this aspect of the EHA system.

9.1. Thermal analysis

Due to the compactness of the EHA system, there is minimum heat exchange. Therefore, it is important to facilitate temperature prediction at an early stage of the design process. The analysis of the heat



BLDC - BrushLess Direct Current; FDBP - Fixed Displacement Bidirectional Pump

Figure 9. Fault-tolerant hydraulic actuators (Muenchhof *et al.* 2009).

generation and dissipation in an EHA system can be implemented by building the temperature field model of the EHA system. The temperature field model of the motor can be built by the finite element method or the equivalent thermal network method. The temperature field model can be built by the equivalent thermal circuit method (Kong *et al.* 2011). Powell *et al.* (2007) described and introduced a method of modelling heat flow in rotor of electrical machines and a novel technique for lumped parameter representation of the transient thermal behaviour of hydraulic fluid. Modelling in such tools improves the accuracy of analysis level without increasing drastically the complexity of the model implementation.

Andersson *et al.* (1999) studied two concepts of EHA in order to examine the necessity of a heat exchanger. Thermal modelling and simulation of hydraulic components have been done under various operating conditions and concluded from the results that the fluid temperature will vary depending on duty cycle and ambient temperature. Chen *et al.* (1995) have developed lumped-parameter EHA thermal models to characterise component heat transfer within their operating environments using realistic actuator duty cycles generated from six Degree-of-Freedom aircraft simulation.

9.2. Thermal management

The thermal modelling and analysis and its utility in developing a thermal management techniques for a flight worthy EHA has been described by Chen *et al.* (1995). The actuators are mostly used in rarefied atmosphere where heat cannot be easily dissipated through convection. It can only be dissipated through conduction and radiation at the position where the actuator is installed. The conventional centralised Environmental Control System cooling approach may need to be augmented with local thermal control techniques and improved heat sinks to eliminate any requirements for coolant lines running all over the aircraft. The effectiveness of heat sinks can be studied from the thermal models as described above. Efforts to reduce the problem of heat generation at the source can be attempted if the power loss of EHA can be reduced as detailed in (Fu *et al.* 2011). In the EHA the main heat source is the iron loss of the stator iron core and the copper loss of the stator winding. The heat generated depends on the current in the stator windings, the rotation speed and the dimensions of the motor. Hence motor efficiency plays an important role in achieving the required thermal economy. The motor has different efficiencies under different speeds and torques. If the pump displacement is varied according to the speed requirement of the actuator, then the motor can be allowed to operate more or less near the higher efficiency operating point (Fu *et al.* 2011). This way the heat dissipated by the motor can be reduced.

The pressure drop in pumps and valves also generates heat, the amount of which depends on the mechanical dimension of these parts, the density and specific enthalpy of the hydraulic oil. The necessary thermal economy for the actuator can be obtained by properly sizing the accumulator. If the load cycles require short term peak power only with sufficient time for cooling down, the heat capacity of the actuator casing including hydraulic fluid can be used to minimise its size.

The energy loss can also be reduced by optimising the control algorithm of EHA for aircraft use. In EHA-VPVM configuration of the EHA, the displacement and rotating speed of pump can be adjusted simultaneously. The dynamic response becomes faster as the steady-state rotating speed increases but the energy loss becomes more. Fu *et al.* (2011) suggested an optimum control algorithm for the EHA-VPVM configuration in aircraft application so that system has fast dynamic response during take-off and landing and higher efficiency and less energy loss when aircraft cruises.

10. Design optimisation

The design of the EHA has to be optimised based on the mission requirements and on the specific application. Two approaches, *viz.*, optimisation for energy efficiency and optimisation for performance, have been described below.

10.1. Optimisation for energy efficiency

EHA system may be more efficient than traditional hydraulic systems. But there is definitely a scope for optimisation of their design in order to get a more energy efficient systems. For example, the efficiency of the EHA depends strongly on the load conditions, with significantly low efficiency under conditions of partial load which occur when either the desired velocity or load is much less than its maximum value. Ho and Ahn (2010) presented an energy regeneration scheme that can be applied to electro hydraulic actuator which makes it highly efficient even under partial load conditions. Here hydraulic accumulators used for energy recovery can be decoupled from or coupled to the circuit to improve the efficiency of the system in varying speed, and torque situations.

Parameter variation can be studied for its effect on the system efficiency for a specific application. Bond graph structure facilitates the study of parameter variations, making it convenient to size components and optimise a complete system (Li and Wang 2010).

The model of the multidisciplinary coupling characteristics can be applied to Multidisciplinary Design Optimisation (MDO) of the EHA system. The flow chart of the MDO is shown in Figure 10 (Li and Wang 2011). The analysis process, the objective function and the constraint condition can be obtained from the multidisciplinary coupling model of the EHA system.

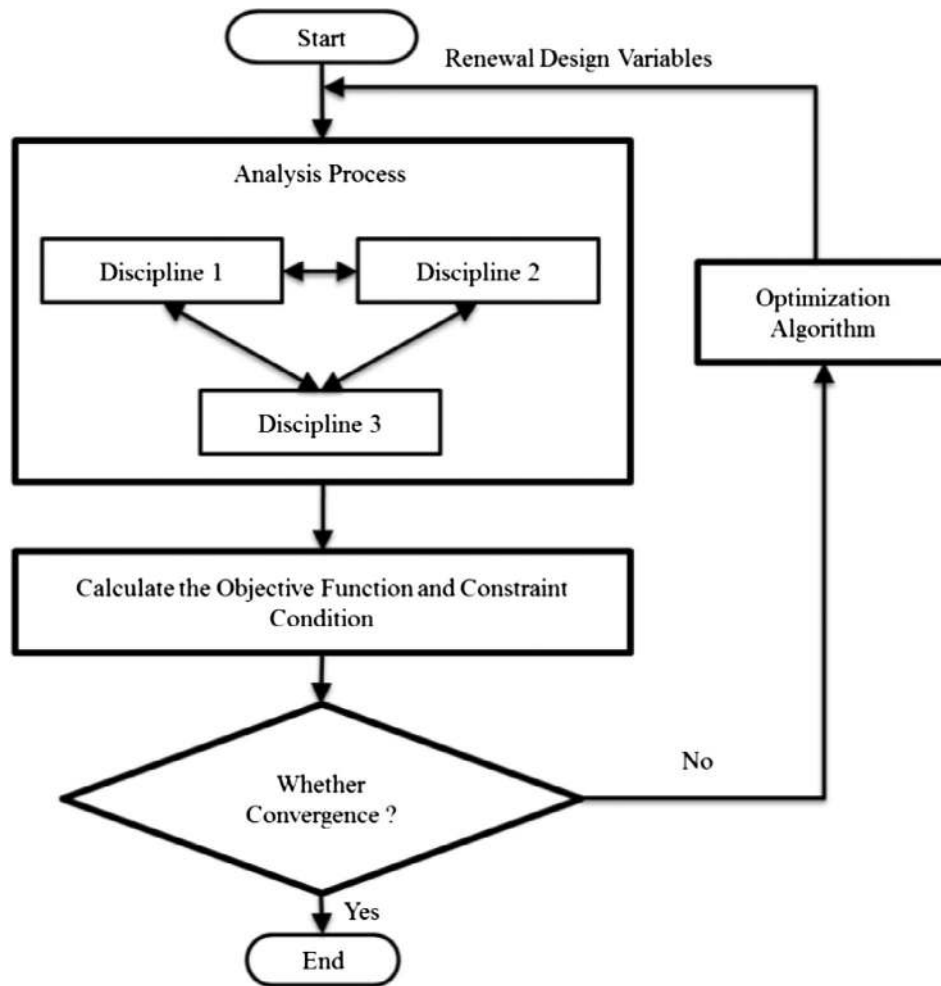


Figure 10. Steps for MDO (Li and Wang 2011).

10.2. Optimisation methods for performance and reliability

Traditional design and optimisation methods for EHA consider performance and reliability requirement separately. They may lead to stable and good performance, but designed scheme may be sensitive to the environment fluctuation, internal parameter variation and component catastrophic failure. Zeng *et al.* (2009) developed an integrated design optimisation method which integrates performance and reliability requirements into the design process. A mathematical model for an Electro-Hydrostatic Actuator (EHA) has been made first and then injected uncertain characters of parameters variation, component failure and disturbance from environment based on their distributions and mission profile. After that, a response surface between the reliability and the system Design Dependent Parameters (DDP) has been created based on the simulation and performance results, thus producing optimised DDPs, which can deliver maximum reliability and meet the performance requirements. Hegde *et al.* (2013) developed optimisation architecture of EHA for aircraft flight control with constraining flight conditions and load cases.

11. Applications

Aerospace industry in the last decade has dedicated itself to the development of greener aircrafts in the commercial transport (Mare 2010). PBW actuators such as EHAs, Electro-Backup Hydrostatic Actuators (EBHA) and EMA principally in backup mode for primary and secondary flight controls have replaced the conventional Servo Hydraulic Actuators (SHA).

Several other applications of EHA have been reported in the literature. Irving and Stephen Smith (2006) have developed EHA, which has been used in F18 Stabilator. Fault tolerant EHA developed by Moog Inc. has been used for thrust vectoring control. Airbus has tested EHA for inboard aileron on A340 in 2002. The latest Airbus A380 uses EHA to actuate ailerons (Le Tron 2007). Takahashi *et al.* (2008) developed an EHA prototype for Landing Gear Extension and Retraction System (LGERS) application.

12. Conclusions

This paper has tried to consolidate the research work carried out so far on Electro Hydrostatic Actuator (EHA) system and presented the state-of-the-art technology specific to flight control application. From the review

of the references, several aspects on EHA system are noted and summarised below:

- EHA technology has matured considerably.
- EHA is a viable option for an efficient, reliable and maintainable PBW hydraulic actuation system.
- EHA has been used in the latest generation of military and commercial transport aircraft.
- Most of literature indicates the growing importance of EHA. Several authors have published their work on EHA. The major aspects addressed by the authors have been on configuration design, modelling and simulation approaches, control strategies, fault tolerance and thermal analysis.
- Initial research into this field aimed at achieving the same level of positional accuracy as servo valve controlled hydraulic systems.
- To enable it to be successfully used for aerospace application, the EHA will be required to have high positional accuracy and dynamic response, reliability and fault tolerance.
- Cost, energy efficiency and thermal stability have to be taken into account during the design stage.
- VPVM configuration of the EHA is capable of providing the required efficiency as well as high dynamic response.
- Motor and power inverter technologies have matured sufficiently.
- Advanced nonlinear control strategies have made it possible to achieve the required positional accuracy under varying flight conditions.
- Latest analytical redundancy and reconfigurable FTC techniques can be used for realising an intelligent, reliable and cost effective EHA system.
- The future research in the field of EHA will be directed towards stronger and lighter materials, higher pressures and better control along with fault tolerant systems.
- A most revealing feature is that almost minimal work has addressed on the development of energy optimised configuration, failure modes, redundancy strategies and approaches for integrated vehicle health management.

The reference attempts to cover the technical literature in English language for slightly more than two decades, 1990's to 2015. There may be of course other work in the field that has been published in other languages, particularly in German, Japanese, Chinese and Russian. The criterion used to include a reference has been whether it would be available from a major technical university library or e-journals. Unpublished internal reports, unpublished conference proceedings etc. are not cited in this paper. In a field with so many inter-disciplinary interactions, selection mainly focuses on fluid power systems and control which reflects the primary interests of the authors.

List of acronyms

ABS	Adaptive Back-Stepping
BLDC	Brushless DC
DAC	Direct Adaptive Controller
DDP	Design Dependent Parameters
DISO	Dual Input Single Output
DOF	Degrees of Freedom
DSP	Digital Signal Processing
EBHA	Electro-Backup Hydrostatic Actuator
ECS	Environmental Control System
EHA	Electro Hydrostatic Actuator
EKF	Extended Kalman Filter
EMA	Electro Mechanical Actuator
EMI	Electro Magnetic Interference
EPAD	Electrically Powered Actuation Design
FBW	Fly-By-Wire
FDI	Fault Detection and Identification
FDBP	Fixed Displacement Bidirectional Pump
FLC	Fuzzy Logic Controller
FNN	Fuzzy Neural Networks
FPVM	Fixed Pump Variable Motor
FTC	Fault Tolerant Control
IAC	Indirect Adaptive Controller
IAP	Integrated Actuator Package
IGBT	Insulated Gate Bipolar Transistor
IMM	Interacting Multiple Model
IPM	Internal Permanent Magnet
ISIDF	Inverse Sinusoidal Input Describing Function
KF	Kalman Filter
LGERS	Landing Gear Extension and Retraction System
LVDT	Linear Variable Differential Transformer
MDO	Multidisciplinary Design Optimisation
MISO	Multiple Input Single Output
NRV	Non Return Valve
OOM	Object Oriented Modelling
PBW	Power-By-Wire
PID	Proportional Integral Derivative
PMSM	Permanent Magnet Synchronous Motor
PRV	Pressure Relief Valve
PWM	Pulse Width Modulation
PWM-VSI	Pulse Width Modulation – Vector Source Inverter
QFT	Quantitative Feedback Theory
RBFNN	Radial Basis Function Neural Networks
SAC	Simple Adaptive Control
SHA	Servo Hydraulic Actuator
SMC	Sliding Mode Control
SMCF	Sliding Mode Controller and Filter
SPC	Scheduled Proportional Controller
SPM	Surface Permanent Magnet
SVSF	Smooth Variable Structure Filter
VPFM	Variable Pump Fixed Motor
VPVM	Variable Pump Variable Motor
VSF	Variable Structure Filter

Disclosure statement

No potential conflict of interest was reported by the authors.

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