

Electrical Accumulator Unit for the Energy Optimized Aircraft

Jason R. Wells, M. Amrhein and E. Walters
PC Krause and Associates, Inc.

Steve Iden, Austin Page and Peter Lamm
US Air Force Research Laboratory

Anthony Matasso
Lockheed Martin Corp

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ABSTRACT

The movement to more-electric architectures during the past decade in military and commercial airborne systems continues to increase the complexity of designing and specifying the electric power system. In particular, the electrical power system (EPS) faces challenges in meeting the highly dynamic power demands of advanced power electronics based loads.

This paper explores one approach to addressing these demands by proposing an electrical equivalent of the widely utilized hydraulic accumulator which has successfully been employed in hydraulic power system on aircraft for more than 50 years.

INTRODUCTION

The movement to more-electric architectures during the past decade in military and commercial airborne systems continues to increase the complexity of designing and specifying the electric power system. The addition of numerous high-power electric loads has drastically altered the dynamics of power flow on the electrical bus. Many of these loads often exhibit peak-to-average power ratios in excess of 5-to-1 for brief periods of time (50-5000 ms). In addition to this high peak-power, some of the loads can produce regenerative power flow equal to peak power draw for brief periods of time (typically 20-200 ms).

There exists a wide variety of architectures which are capable of addressing the challenges of this dynamic power profile. For example, one architecture is to force regenerative power to be handled locally with diodes / power resistors and to size the generator (including the gearbox, shafts, etc.) to be capable of peak power generation. Such architecture can be challenging to design and may lead to an unnecessarily large increase in system weight due to increased demands on the thermal systems and derating of key mechanical components in the generator drive-train. Another viable approach is to allow the electrical bus to support

bidirectional power flow all the way back to the engine. Aircraft generators often already have the requisite power electronics to support bi-directional power flow due to their dual role of providing main-engine start capability. While this approach reduces the thermal concerns associated with burning regenerative power locally, it actually increases the derating factors required in the mechanical drive-train of the generator which again could result in increased system weight.

The focus of this paper is another alternative wherein an electrical accumulator unit (EAU) can be placed on the power bus to provide peak-power fill-in and regenerative power absorption capabilities. Such an approach is similar to the hydraulic accumulator units (HAUs) which have been used in previous aircraft to address similar issues which arise when primary flight surfaces are driven by hydraulic actuators [1-3]. It enables a bi-directional power bus (and hence a reduction in thermal concerns related to burning regenerative power locally) without suffering an increase in the derating factors utilized in the mechanical drive-train. Additionally, it can reduce the peak-power demands on the generator allowing either a reduction in weight of that system or an expansion of electrical power system (EPS) capabilities. In addition to these key benefits, it may also enable full flight surface performance even under emergency power conditions (often the emergency power sources are not capable of supplying high peak-power necessitating power-limited operation of actuators). In emergency mode, the primary sources (e.g., battery) are only required to supply the average power of the actuators due to load-leveling provided by the EAU.

This paper first presents a representative dynamic power transient which might be seen on a modern more-electric aircraft to illustrate the dynamic power challenge. Next, the paper outlines the fundamental concepts of EAUs and explains their underlying similarity to the hydraulic accumulator. To demonstrate the viability of such an EAU concept, a specific EAU is designed and modeled in the Matlab / Simulink environment with the Graphical ASMG toolbox [4]. Finally, the paper presents simulation

results of the proposed EAU under a variety of operating conditions.

POWER DYNAMICS ON MODERN MEA

As mentioned in the introduction, there exist several loads on modern more-electric aircraft (MEA) which present highly dynamic power draw characteristics to the EPS beyond levels typically seen in previous aircraft. Such loads include electro-hydrostatic actuators (EHAs), electromechanical actuators (EMAs), advanced radar, and directed energy weapons (DEW). Although these loads represent a relatively small portion of the average power draw from the EPS, the short-term transient power may exceed twice the average power capabilities of the generator. In addition to demanding large peak power, EHAs and EMAs can regenerate significant power during deceleration of motors and drive train.

Figure 1 displays a representative power profile which might be seen on a modern MEA during a significant aircraft maneuver. This figure illustrates the large swings in dynamic power which can occur; however, these transients typically occur for brief periods of time between periods of time with significantly reduced dynamics.

EAU ARCHITECTURAL DESCRIPTION

Although the EPS generator could be sized to accommodate the peak and regenerative power transients described in the previous section, this would likely result in a significantly oversized architecture imposing an unnecessary weight penalty to the aircraft. Instead, it is proposed that some portion of the peak transients be accommodated by an EAU with the remainder provided by the generator system. The exact distribution of power delivery capabilities is highly dependent upon the specifics of a given aircraft application; however, a potential distribution is illustrated in Figure 1 wherein the EAU provide up to 1 pu (based on generator average power rating) peak bidirectional power capability.

Figure 2 depicts both a hydraulic and an electrical power system with an included HAU/EAU, respectively.

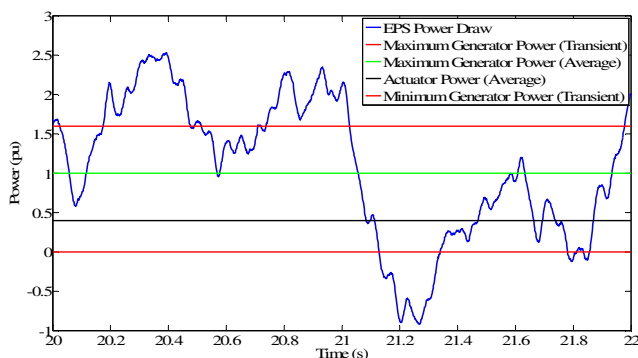


Figure 1. Transient power profile in a representative modern MEA.

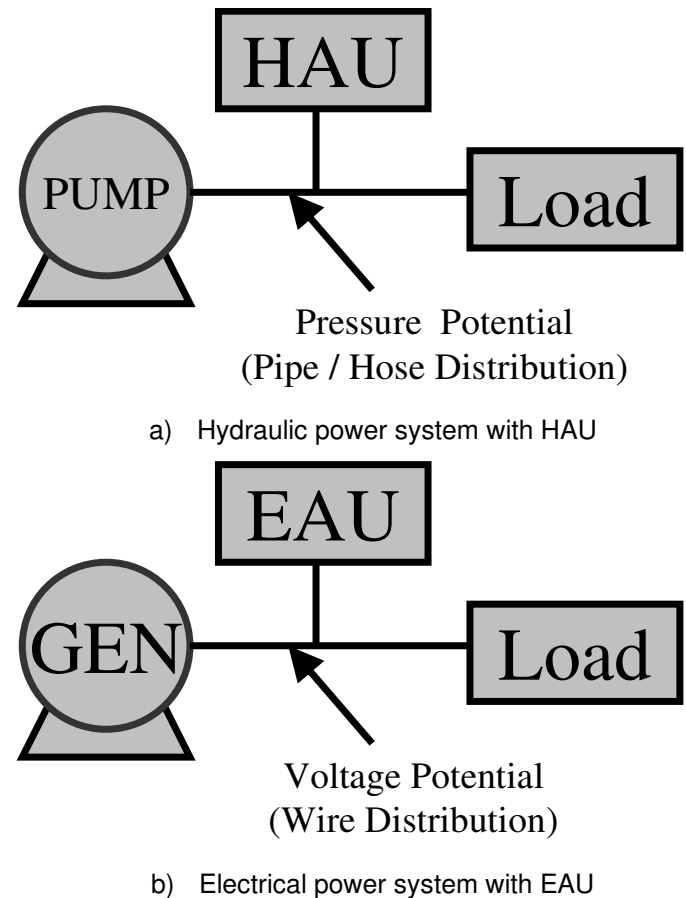


Figure 2. Transient power profile in a representative modern MEA.

Although the HAU/EAU are depicted in parallel on the distribution system, it is also possible to place them in series between source and load. In both the HAU and EAU, an energy storage mechanism is included in the accumulator unit such that the potential on the distribution system can be maintained through large transient demands by the load without requiring the primary source to be upsized.

A variety of energy storage mechanisms exist for both the HAU (e.g., compressed gas, springs, metal bellows, etc.) and the EAU (e.g., electro-chemical [battery], capacitive, inductive, electromechanical [flywheel]). Each of the mentioned storage mechanisms will offer a different set of advantages / disadvantages which must be considered when designing for a given application. Typically, in aircraft applications weight is a primary concern followed closely behind with volume (though the optimization of both are usually closely linked). As such, the specific power, specific energy, and cost for each of the technologies will likely drive the decision to use one technology over another.

In the case of the HAU, the accumulator unit control of the energy storage device (ESD) is often passive. In the EAU, a similar configuration can be imagined wherein an ultra-capacitor or battery is connected directly to the bus and the power flow in to or out of the device is uncontrolled. Such a passive approach is likely to offer

performance advantages for the fastest of transients; however, the addition of a power-electronic converter is likely to offer performance advantages in terms of controlled ESD utilization across a variety of operating conditions (temperature, state of charge, fault conditions, etc). Depending upon the specifics of the storage / power capabilities of the EAU, it is possible that the addition of such a power controller will actually reduce the total weight of the EAU compared to a purely passive approach. In addition to offering potential weight advantages, the addition of a power controller enables several advanced functionalities to be included in the controller. Ultimately, the optimal EAU may include both a small passive ESD to handle extremely fast transients and a larger controlled ESD to provide peak power assist and regenerative energy absorption capabilities.

ULTRA-CAPACITOR BASED EAU DESIGN

To illustrate the proposed controlled EAU approach, the authors are currently involved with the design, construction, and test of a prototype EAU capable of sourcing / sinking 100 kW with a usable energy storage capacity at least 150 kJ. The basic layout of the proposed EAU is illustrated in Figure 3. The following sub-sections will outline the design of the unit which is currently under construction. The model development has been performed utilizing the Graphical ASMG toolbox for Matlab / Simulink.

Energy Storage Device

For the desired ESD energy capacity and power rating, both lithium ion batteries and ultra-capacitors were considered as candidates for the ESD. Utilizing the specific power and energy numbers from the commercially available Maxwell Technologies BCAP0650P270 ultra-capacitor (3.29 Wh/kg, 15.1 kW/kg) [5] and the Saft VL7P lithium ion cell (67 Wh/kg, 1.811 kW/kg [from data sheet with 10s rating], 5.73 kW/kg [estimated 1s rating]) [6] the estimated mass of ESD required to meet specifications can be calculated. It is assumed that only 75% of available energy storage can be utilized in the ultra-capacitor due to power converter design considerations and that only 50% of the

available capacity of the battery can be utilized due to component life considerations.

Battery:

$$W_{battery}^{energy} = \frac{(150,000 \text{ Ws}) \left(\frac{1 \text{ hour}}{3600 \text{ s}} \right) \left(\frac{1 \text{ kg}}{67 \text{ Wh}} \right)}{(50\% \text{ Energy Utilization})} = 1.24 \text{ kg} \quad (1)$$

$$W_{battery}^{power} = (100,000 \text{ W}) \left(\frac{1 \text{ kg}}{1,811 \text{ W}} \right) \left(\sqrt{\frac{1 \text{ s}}{10 \text{ s}}} \right) = 17.46 \text{ kg} \quad (2)$$

Ultra-capacitor:

$$W_{battery}^{energy} = \frac{(150,000 \text{ Ws}) \left(\frac{1 \text{ hour}}{3600 \text{ s}} \right) \left(\frac{1 \text{ kg}}{3.29 \text{ Wh}} \right)}{(75\% \text{ Energy Utilization})} = 16.89 \text{ kg} \quad (3)$$

$$W_{UCap}^{power} = (100,000 \text{ W}) \left(\frac{1 \text{ kg}}{15,100 \text{ W}} \right) = 6.63 \text{ kg} \quad (4)$$

Based upon the above analysis, wherein the minimum mass required to satisfy both power and energy storage specifications favors the ultra-capacitor, and the considerable difference in cost, the decision was made to construct the prototype EAU utilizing ultra-capacitors. The current design utilizes a 100 cell series stack of the BCAP0650P270 cells with a target nominal charge level of 250 V_{dc}.

Power Electronic Converter

After the ESD configuration had been determined, a power electronic converter suitable for providing the interface between the ESD and the EPS distribution bus was designed. Although a large number of power electronics topologies would be suitable, the topology implemented is based upon [7, 8] and was chosen for the soft-switching advantages and reduction of power passive component sizing in the EMI filter stage.

The first step for the design of such a converter is to

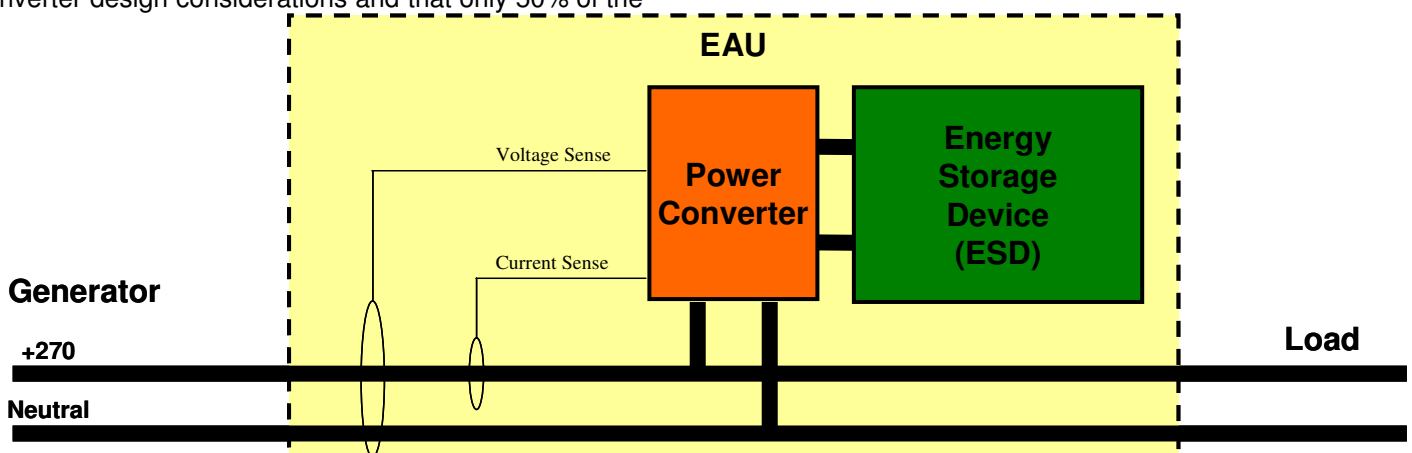


Figure 3. Proposed EAU layout