Energy Management of Aircraft Electrical Systems - State of the Art and Further Directions

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AEA	All Electric Aircraft
APU	Auxiliary Power Unit
BPCU	Bus Power Control Unit
DAL	Design Assurance Level
ECS	Environmental Control System
ELM	Electrical Load Management
EM	Energy Management
GCU	Generator Control Unit
MEA	More Electric Aircraft
SOC	State Of Charge
SRL	Slow Responding Load
SSPC	Solid State Power Controller
WIPS	Wing Ice Protection System

***Abstract*—This review paper summarizes state-of-the-art energy management methods applied to electrical systems of large aircraft. An electrical load management based on fixed priorities of the loads is considered a conventional implementation as applied in today's aircraft systems. It can cut and reconnect loads depending on their importance. The advantages and disadvantages of such a system are presented. Further implementations are depicted that are able to eliminate certain drawbacks of such a typical load management. Most promising is the exploitation of so-called slow responding loads which can be handled like an electrical storage. The optimization potential on future energy management functions is finally discussed and conclusions are drawn.**

I. Introduction

For decades there has been an ongoing trend toward more electric aircraft (MEA) like the Boeing 787 or Airbus A380 (see [1], [2], [3]);]); recently, the trend has even included all-electric aircraft (AEA). Electrically driven systems such as ice protection, environmental control system (ECS), brakes, or primary flight control system actuators have been used instead of their conventional counterparts [4]. The advantages of MEA are:

- Electrical systems usually have a higher efficiency.
- Simultaneity effects can be exploited since power is distributed through one and not three physical domains.
- Power just needs to be produced when it is used and not throughout the flight, thus resulting in higher energy efficiency.

However, a critical issue of MEA is the weight of the needed electric components and systems as discussed in [4]. Thus, weight reduction is one the main drivers for future aircraft systems [5],[6].
Typical electrical power distribution architectures as applied in today's aircraft can be found in [7] and [8]. They consist of generators, converters, feeders, bus bars, switches, and similar components. Since MEA often switches from constant frequency to 3-phase wild frequency networks, generators cannot be paralleled. This lack of parallelism decreases the simultaneity effect, since several stand-alone power distribution networks are needed. Hence, in [9] and [10], high voltage dc and mesh networks have been investigated that enable parallel sources and reduced system weight.
Another point is that the current way of dimensioning the electrical distribution system during design shall be revised. As shown in [11], this has been done by taking the maximum power of each load and calculating the sum for each flight phase so far. This approach leads to little usage of the available generator capacity. Future electrical systems shall thus be dimensioned by a different approach–for example, by statistically analyzing power consumptions [12].
All the facts mentioned above illustrate that an improved energy management function is also needed for future electrical systems to prevent power peaks and overloads of electrical system components. Improved management functions allow reducing system weight and increasing overall efficiency. This paper investigates available energy management methods for aircraft electrical systems and subsequently draws conclusions for future implementations in order to optimize the energy management.

A. Terminology

In the literature and in everyday language, different terms have been established for the functions or methods that control an electrical system. The first one is *energy management* (EM), which is the umbrella term for each method or system that controls energy flow. It has typically been used for systems containing a storage device, like the electrical system of automobiles, or standalone systems having a battery as the single power source.
Conversely, the term *power management* has often been used

for electrical systems having no or no relevant storage devices. Thus, a typical power management function has to ensure that the power generated in any instant in time is equal to the consumed power. This power balance is mostly the case in current aircraft electrical systems, since the available batteries are only employed for emergency operation or for starting the auxiliary power unit (APU). Furthermore, the term *electrical load management* (ELM) is often used for aircraft, since those functions can only control loads and not generators.
The term *source management* can be used if several power sources are available and controllable. Those functions often control multiple sources so that optimal energy efficiency of the entire system is reached.
Even though the term *power management* seems to be the one most suitable for aircraft electrical systems, we choose *energy management* in the following, since this term is more general. Furthermore, future aircraft electrical systems may also include storage devices, as shown below.

B. Degree of Freedom

This section will list the system variables an energy management can control and thus its degree of freedom.

- Electrical loads can at least be cut off or reconnected (on/off). There are also loads that can be regulated continuously or incrementally.
- Generators can often operate above their nominal power for a short time. This overload capacity can be exploited.
- The energy management can split the power demand of a set of loads on several sources if parallel sources are available.
- The configuration of the network can be adjusted (i.e., which generator is connected to which sub-network or bus bar).
- Storage devices can take or provide prescribed power, if available.

Consequently, the optimization potential of energy management functions strictly depends on the complexity and dimension of the respective system.

II. Typical Implementation

This section describes a typical implementation of an energy management of current aircraft electrical systems. The task is split into different sub-tasks as illustrated in Fig. 1. The generator control unit (GCU) controls the operation of the generator circuit breaker aside from other functions. Thus, it can open the circuit breaker in case of a non-tolerable overload. The bus power control unit (BPCU) can close or open bus tie breakers or auxiliary power breakers to tie two bus bars together (e.g. AC2 and AC3) or a bus bar to another generator if a generator is lost or not available [8].
The most complex function is the electrical load management. It ensures that no overload occurs during operation by cutting loads. Here, each controllable load has a fixed, predefined priority. The higher the priority of a load the later it will be shed. To determine the amount of loads to be shed, current or

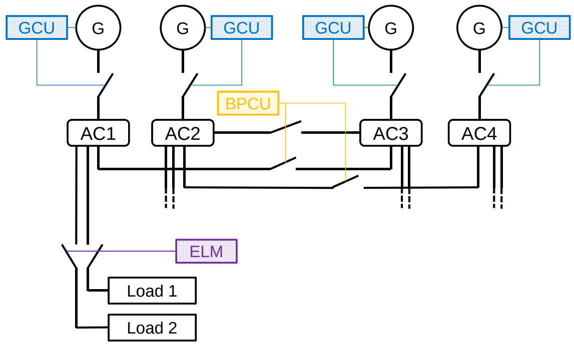

Fig. 1. Typical functions controlling the electrical system.

power of the generators and the loads is measured. Additionally limits like current thresholds of feeders and converters can be controlled in the same fashion. It should be noted that “one load” for an ELM doesn’t have to be a single load. Often a set of similar loads connected to one solid state power controller (SSPC) is meant.
The basic principle of a function detecting overload and disconnecting loads automatically according to a priority list has firstly been mentioned in [13][1]. Prior to this, just circuit breaker boards were available, which had to be reconnected manually via checklist. The basic functionality is also described in [14]. In [15] a typical load management in combination with an interface for the cockpit is depicted, where the crew or pilot can select loads to be connected and with it loads to be disconnected instead in order to remain below power threshold. Furthermore the basic functionality of an ELM is also described in the state-of-the-art of the patents [16], [17], [18], and [19]. Thus, one can state that this type of function is a typical implementation of an ELM.
One point to mention is that there are often many loads having the same priority. Thus, the ELM has to decide by further criteria which loads shall be shed and which not. One way could be to keep as many loads as possible connected resulting in cutting large loads first. Another one is to find a set of loads in a way that as much generator capacity is used as possible. This task is also known as “knapsack problem”.

A. Advantages

There are several reasons why such an ELM has been applied for many electrical systems. The basic implementation is quite easy. One has to define priorities for each load and determine thresholds at which shedding and reconnection take place. Using priorities also several loads having different design assurance levels (DAL) can be controlled by one ELM. Furthermore proven and mature algorithms are available, since it has been applied for decades.

B. Disadvantages and Problems

The intended use of an ELM is to cut and reconnect loads regarding its priority as explained above to prevent overloads.

[1]patent submitted in 1973

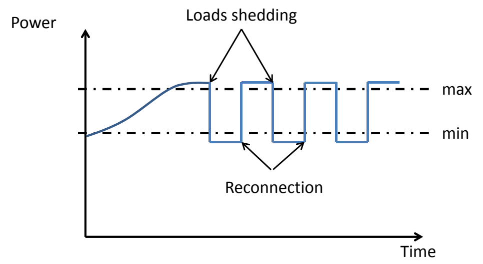

Fig. 2. Instability occurring if max and min power levels are too close.

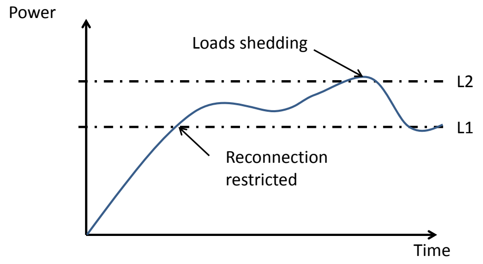

Fig. 3. Illustration of the different power levels as applied in [19].

Thus, it is limited to switchable loads and cannot deal sufficiently with continuously controllable loads. One possibility is to split down continuous loads virtually into several switchable loads in order to control their power consumption in discrete steps.

Furthermore at least two different thresholds for shedding (max) and reconnecting (min) loads are needed as illustrated in Fig. 2. When the power consumption exceeds max, load shedding is initiated. When it is below min, reconnection of loads takes place. Let us now assume a large load that consumes at least $(max - min)$. If the ELM chooses this load to be shed the power consumption will drop below min. Thus, the reconnection is initiated of the same load, which results in an instability since the load is switched on and off periodically as shown in Fig. 2. To prevent this instability one has to decrease the threshold min. Thus, there is always a tradeoff between stability and usable generator capacity. This drawback can be reduced by keeping track of the nominal values of shed loads or the last measured value before the shedding and only reconnect a load if it won't exceed the max-value.

In most cases the importance of a load is not constant during a flight. It can depend on the flight phase or any other condition. Using fixed priorities, as done for a typical ELM, changing importances cannot be taken into account.

Finally, a typical ELM "merely" performs tasks of protecting generators and further components of the electrical system from overloads. Unlike energy management that is described hereafter, ELM is not capable of optimizing overall efficiency or reducing size and weight of the electrical distribution system.

III. Advanced Implementation

Based on a typical ELM, further differing concepts for an energy management method are described in the following.

A. Variable Priorities

To consider the changing importance of loads during a flight one can simply use variable priorities instead of fixed ones. Thus, the priority can be determined by the loads themselves depending on their current importance. Indeed, this would cause an increased communication effort but would allow a more flexible and fair distribution of power. A method using variable priorities has been presented in [20]. Prior to that, the electrical load management could just deal with the galley as one load, which could be simply shed or connected. Thus, a local power management of a galley system is applied. Each load sends a variable request level and its requested power to a controller. The higher the priority or request level, the earlier the load will be connected. Shedding of loads is not foreseen, thus they have to shed themselves if they finish operation or a predefined time is expired. Even though the title of this patent indicates an application merely for an aircraft galley, a method is claimed that can also be applied for the entire electrical system of an aircraft.

B. Supervise Reconnection

Instead of shedding loads if an overload occurs, one can also prevent loads from being reconnected if a dedicated power level is reached. In [18] a load management system is described that provides a "power available"-signal. Thus, if no power is available no further loads will be connected. The advantage of such a function is that the implementation is very easy and it just requires little computational time.

The main drawback is that different priorities of loads won't have any impact on its availability. The method works with a "first come first serve" principle and is thus not applicable for dealing with loads having different design assurance levels (DAL). Furthermore the principle won't work if still connected loads can raise their power without interacting with the management function.

These drawbacks can be resolved by defining additional power levels as done in [19]. There is at least one predetermined power level $L1$, at which no additional load will be reconnected as in [18]. Additionally there is a power level $L2$, which is higher than $L1$. At this level loads can also be shed as shown in Fig. 3. The shedding of loads can now be done using the priorities. But if level $L2$ is not exceeded, still the "first come first serve" principle applies.

Based on a typical priority driven load management there is also a system described in [14] where the reconnection of loads is managed in a way to prevent simultaneous reconnection of several loads using variable delays for the loads depending on the current situation.

C. Source management

If several sources are available that can be connected in parallel one can apply a source management, that controls

the different sources or generators in an energy-efficient way. An intelligent source management will regulate the several sources to reach the least overall power losses. In [21] a source management is shown using e.g. a generator and a fuel cell in parallel. Besides the optimal deployment of electrical energy also further forms of energy like heat shall be used in an efficient way. The energy is then distributed to several loads having a variable priority depending on the flight phase.
For heavy loads there is also a method mentioned in [22] where one load is fed by several sources, which is done by regulating the output voltage of the respective source.

D. Consider Electrical Storage Devices

The degree of freedom of an energy management method increases considerably if electrical storage devices like batteries or supercaps are available. Storages can be used to smooth out the power consumption of load groups. This in turn enables to design lighter generators, feeders, and converters especially in case of many non-constant loads. However, the batteries or supercaps will add weight. Thus, there will be an optimal tradeoff between installed battery-capacity and installed power of e.g. generators to minimize weight. A system having electrical multiple power sources as well as storage devices is shown in [23].
To minimize power peaks during a flight, predictive information is very useful to control the storage device in an optimal way. In [16] and [17] predictive information will be provided via a preset flight profile including relevant events for the electrical system, by using data of recent flights, or by a predictive consumption profile sent by each load. This information will now allow to generate an optimal time-plan for each load, each generator, and each electrical storage. A possible total power consumption of a system depending of a generator and a battery is shown in Fig. 4. Using a battery the maximum available power can be increased for some time resulting in an increased availability of the loads or a lighter design of the generator and possibly converter as well. At the end of a flight the battery should have the same state of charge (SOC) as at the beginning. Thus, the indicated areas in Fig. 4 below and above the generator power output should be equal for a flight and the maximal and minimal SOC of the installed battery has to be taken in to account.
It should be mentioned that in [16] and [17] the power threshold of the generators don't need to be a fixed value. It can depend on the rotational speed of engine and further variables. So the threshold profile can also be predicted using a preloaded flight profile.

E. Exploit Slow Responding Loads

In today's aircraft systems there is a number of slow responding loads. That is systems and components with large time constants like heaters. Since electrical storages will add weight, one can also try to decrease power peaks by exploiting such slow responding loads (SRL). Thus, they can be handled like an electrical storage since they store energy in their respective physical state like the heat of a galley oven.

A method that exploits large responding times of aircraft galleys is claimed in [24]. The reduction of power peaks is realized via time-sharing, power-sharing and peak compression. Time-sharing alternately switches loads on and off as illustrated in Fig 5. Power sharing reduces the consumption of a load in a fashion that a second load can be switched on for a dedicated time. Peak compression avoids the power-on of two loads at the same time. For this purpose predefined procedures are determined for a set of cases to reduce power peaks by keeping full availability of the electrical devices. Also in [16] and [17] loads like ECS or wing ice protection are operated periodically or are shifted to decrease power peaks. Furthermore time-sharing is part of the invention in [25] for domestic controllers.
A more flexible approach can be found in [26]. Here the electrical system is divided into a primary load system having a proprietary controller and a secondary load system controlled

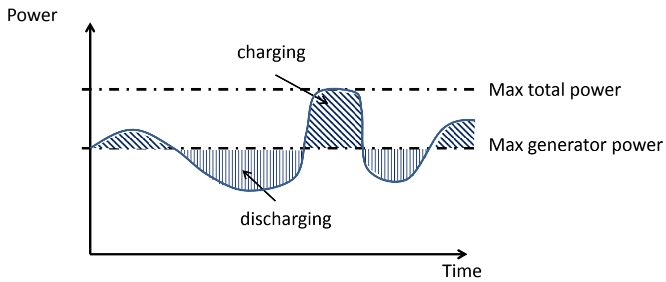

Fig. 4. Example of a total power consumption profile using a generator and a battery in parallel as in [17].

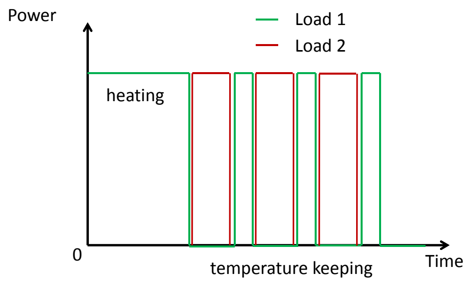

Fig. 5. Typical power behavior of two loads using time sharing.

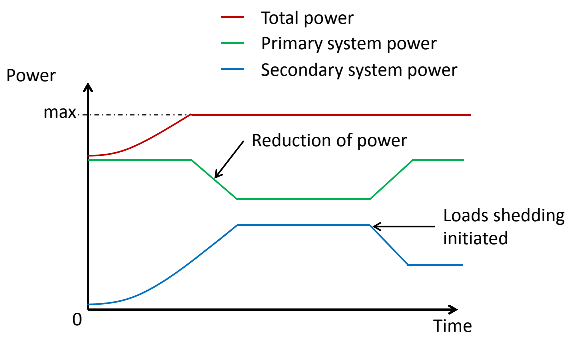

Fig. 6. Controlling electrical power of primary and secondary system as done in [26].

by a conventional ELM. An ECS is a typical primary load system. Depending on cabin temperature and further parameters the ECS controller can decide if and to what extent the power can be reduced as shown in Fig. 6. If the maximum power threshold of the generator is exceeded or is expected to be exceeded the power consumption of the ECS can be reduced continuously by its own controller. The ECS controller and ELM communicate with each other. If a reduction of ECS is no longer possible the ELM cuts loads as in Fig. 6. Thus, this approach prevents power peaks without any impact on the availability of the loads using a slow responding load as far as possible.

IV. Discussion

The previous sections list available energy management methods applicable for aircraft electrical systems. But what is the main conclusion? What does it mean for future EM? The answers to these questions are not trivial. On the one hand a typical ELM is applicable to a large amount of systems. However, on the other hand, for MEA or AEA an optimized and more intelligent energy management is needed to minimize system weight and optimize energy efficiency. Thus, one should consider each of the following points to get an optimized and efficient energy management:

- **Variable priorities:** Since importance of loads can change during operation, variable priorities enable an increased availability of loads that are needed during operation.
- **Stability versus unused generator capacity:** As mentioned earlier, there is typically a tradeoff between a stable management algorithm and usable generator capacity in case of ELM. Thus, methods have to be found that can deal with both in an optimal way.
- **Exploit slow responding loads:** Main benefits can be drawn by exploiting slow responding loads as shown in section III-E. This will allow reducing system size and thus weight by keeping availability of respective loads. Especially heavy loads like galleys as well as electrical driven ECS and wing ice protection system (WIPS) are the ones most suitable.
- **Load analysis:** A detailed load analysis is a key element for future electrical systems. It should be identified which load has which importance depending on its state or the flight phase and if a shedding is perceivable or not. This will be essential information for an energy management function.
- **Electrical storage:** If electrical storages are available, a prediction and optimization of power consumption can increase energy efficiency and decrease system size. Thus, more complex energy managers will be needed.
- **Multiple sources:** If multiple sources are available, one can optimize the energy efficiency of the system by applying a source management.
- **Enable energy regeneration:** In [27] a system is described that enables energy regeneration of electrical actuators instead of dissipating heat at a shunt resistance to enhance energy efficiency. Furthermore system size can be reduced, since no shunt is needed where heat is dissipated and thus no active cooling is required. Hence, one should at least try to allow regeneration of actuators, which is mainly a challenge for the electrical system rather than for the EM function. But an EM should at least not prevent regeneration.

The advantages taken from an improved and intelligent EM have to be compared to the increased complexity, computational effort, and safety considerations in order to obtain an optimal aircraft system.

V. Conclusion

The state-of-the-art energy management methods applicable for electrical systems of large aircraft have been presented. Typical load management functions are compared to other methods that are able to eliminate certain drawbacks of such an ELM. Finally, the optimization potential of future energy management functions has been discussed. Before starting implementation of an energy management function from scratch, EM's that have been applied for other local systems like automotive should be considered especially if electrical storages are available.

As already mentioned, one ought to keep an eye on the complexity and manageability of such a function and the associated system. We think it is at least worth trying to consider all the points mentioned in section IV for future EM and assess its impact on weight and efficiency of aircraft systems, which requires an early and integrated design of the energy management controller in conjunction with the system to be controlled. Thus, modular, object-oriented modeling and simulation is needed at an early stage of the design process to cope with the complexity and exploit the entire potential of an EM. This will be part of future investigations.

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