

A Holistic Approach towards Optimizing Energy Storage Response during Network Faulted Conditions within an Aircraft Electrical Power System

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ABSTRACT

Within aircraft electrical network designs, energy storage systems (ESS) provide a means of decoupling the electrical-mechanical interactions between the aircraft electrical power system and the aircraft engine, meeting peak load demand and maintaining power quality during network disturbances and variable load conditions. Within the literature to date, control and management strategies of ESSs for such applications has primarily focused on normal network operation with only limited coverage on the behavior of such technologies under abnormal conditions and the subsequent impact on the operation of the wider power system. Through modeling and simulation of a generic aircraft electrical system, this paper will highlight the potential risks of the inherent, sub-optimal operation of certain existing control strategies during fault conditions. It will also discuss the sensitivity of the integrated system response to a number of technological factors including the ESS and wider network converter topologies, protection and control system design, and operational modes. To this end, a holistic approach to optimizing the behavior, control and protection of energy storage during both normal and network faulted conditions is of considerable interest. The paper will discuss what 'optimal' may mean in this context and will explore the varying extent to which system-level optimization may be achieved. It will also explore the opportunities for the utilization of energy storage to enhance overall network behavior during faulted conditions, for example by capitalizing on the intrinsic sensitivity of the ESS to fault transients as a potential early indicator of a network fault. The paper concludes by emphasizing the substantial research opportunity presented within the aerospace sector and other related domains where the expected near term solutions will focus primarily on modest developments to application specific ESS hardware and control. In the longer term, the development of an optimized integrated system-level control and protection solution incorporating ESS operation will be the definitive research goal.

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INTRODUCTION

Recent years have seen a rapid increase in the widespread adoption of more-electrical equipment on future defense and commercial airborne systems [1]. Electrical power distribution networks will supply proportionately greater levels of electrical loading than on present-day designs and are likely to integrate greater quantities of power electronic converter interfaces with increased control capability. Furthermore, employment of global electrical power distribution architectures in place of conventional hydraulic and pneumatic systems will offer potential benefits in overall system design flexibility and operational capability [2, 3].

Such modifications however, create a number of additional electrical system design challenges. Two

challenges with particular relevance to the integration of energy storage on a network are the management of network power quality and the system response to large load transients. While the employment of solid state power controller (SSPC) modules may provide some improvement in power quality during load activation/deactivation [4], commercially available devices still only apply at low voltage levels, therefore switching relatively large loads located on higher voltage distribution buses may still cause significant electrical transients. These events may potentially degrade power quality to sensitive loads integrated on the wider system and may impact aircraft engine performance [5]. There is therefore a significant benefit in providing an additional, fast acting, bidirectional energy storage system to support highly transient loads [6, 7].



Energy storage systems (ESS) are also being considered to decouple the interactions between the electrical power system and the aircraft engine, to meet peak load demand, to maintain power quality during network disturbances and variable load conditions, and to increase overall system efficiency. In order to fulfill and optimize these proposed functions, the requirement of more advanced hardware with increased control capability is needed.

Whilst these advantages exist for the normal operation of the network, it is also important to consider the impact of an ESS response during abnormal network events (e.g. faults), an aspect of ESS design which does not feature heavily in current literature. It is clear that the integration of energy storage systems should not compromise the safety of the aircraft power system during such events. Beyond this, the authors believe an opportunity exists to optimize the system-level response of the ESS during such conditions and this is a key argument presented within later sections of the paper.

This paper will highlight how the inherent response of certain conventional ESS control strategies to particular network faults can have a potentially detrimental impact on the network performance. It will show that during such conditions, the storage element can continue to discharge into the fault and contribute significantly to the energy delivered at the point of fault whilst needlessly depleting state of charge. In doing so, examples will be shown where fault detection sensitivity is also reduced at various locations on the network due to the storage discharging, which may hinder the capability of network wide protection devices/functions and may even hinder fault detection by other critical network systems. To this end, a holistic approach to optimizing the behavior, control and protection of energy storage during both normal and network faulted conditions is of considerable interest. The paper will discuss what 'optimal' may mean in this context and will explore the varying extent to which system-level optimization may be achieved, taking into account various technological and operational constraints. It will discuss the sensitivity of the integrated system response to a number of factors (some of which may even vary dynamically for a given application) that may influence the obtainable optimal network performance including the employed ESS and wider network converter topologies, the protection and control system design, and the ESS operational modes at the time of fault inception.

It will then go on to explore the opportunities for the utilization of energy storage to enhance overall network behavior during faulted conditions, for example by capitalizing on the intrinsic sensitivity of the energy storage system to fault transients as a potential early indicator of a network fault. It will explore potential ESS behavioral strategies that may be adopted to enable a more optimized wider system response during abnormal conditions. Finally, this paper will emphasize the substantial research opportunity presented within in the aerospace sector and other related domains and will highlight the expected near term and longer term solutions to achieving this optimal performance.

ENERGY STORAGE

Energy storage within aircraft systems is conventionally employed to supply backup power for flight critical loads in the event of primary generation failure, and usually takes the form of energy dense battery systems. However more advanced energy storage systems with increased functionality can play a number of additional roles within electrical power distribution systems. For example, energy storage systems have been demonstrated in assisting in power management strategies for islanded electrical networks, which has led to significant interest in their integration into applications such as hybrid-electric vehicles, shipboard electrical systems and microgrids [8, 9, 10]. The primary function of the energy storage in these applications is to ensure that load demand is met whilst maintaining the quality of power distribution, for example, maintaining the voltage and/or frequency under variable load conditions or to increase overall system efficiency. Potential reduction in generation capacity may also be achieved in certain applications, where the generators do not require to be rated to output the peak electrical demand [11]. However, any reduction in overall system weight and volume as a result of this will largely depend on the trade-offs with the requirements of the ESS.

To enable energy storage to become more effective for use on aircraft electrical networks, a combination of both battery and supercapacitor systems are being considered [12]. Each of these storage mediums has a distinct dynamic performance. The power density and charge/discharge life cycle of supercapacitors is considerably greater than that of battery systems, whereas the energy density of batteries can be up to two orders of magnitude greater than supercapacitors [13]. Thus, employment of both storage mediums can be complementary, providing the capability for both fast transient mitigation (which can benefit both engine and electrical system operation) as well as a longer term backup supply, potentially extending the range of possible applications within the aircraft electrical system.

While there has been considerable emphasis on the development of control strategies of energy storage during normal network operation for these applications, there is limited coverage within the literature about how these technologies will behave under abnormal operating conditions and how this will impact the system as a whole. For example, the occurrence of a short circuit fault often causes under-voltage conditions on a network. In the case where an energy storage control system is reliant on the measurement of this network voltage, such under-voltage conditions may trigger the rapid discharge of the energy storage into the fault in an attempt to maintain the voltage level. This would potentially cause greater damage at the point of fault and unnecessarily dissipate the stored energy.

Such drawbacks are often overlooked in the design of ESS control systems and offer a potential area for further investigation. For example, the control of ESS in [9] and [10] to automate power balancing and voltage sag correction

during grid connected AC faults is demonstrated. They do not however fully investigate the impact of this operational mode during more severe faults within the DC microgrid. Authors in [14] consider the use of energy storage primarily for fault ride-through of generator phase faults, however greater value could be derived from the proposed control system if the implications of the ESS response to electrical faults within the network was also taken into account.

Fault studies of a low voltage DC microgrid integrated with battery energy storage were conducted in [15], where commercial circuit breaker technology is suggested for protecting the battery ESS during network faults. However, the response of the ESS during the fault studies conducted in this case is uncontrolled, which may significantly change the requirements and operational behavior of the proposed protection system. Accordingly, there are substantial research opportunities that exist in the longer-term development of a fully optimized integrated system-level solution to ESS operation. This will initially include defining what is meant by optimal in this context. For example, the optimum response to two identical faults that are both at a similar distance from the ESS, but occur in different sections of a network, may be considerably different.

The following section aims to address some of the shortcomings of conventional ESS control strategies during more severe electrical faults in order to assess the technological constraints and identify the enablers to optimize the system response.

CASE STUDY

The following case study aims to determine the potential impact of an ESS on the network behavior of a generic aircraft electrical system during simulated fault conditions. For the duration of the simulation, the ESS operates with the control mode described in the following section, designed to mitigate the effect of load transients on the network.

The network response to high impedance faults placed in various locations within this network will be presented and discussed further in the later sections of this paper. The potential effect on network fault detection algorithms and subsequent operation of protection elements will then be discussed. The key critical factors identified through the fault response analysis process will be highlighted, and key areas for future research in the ESS control system design for abnormal operating conditions outlined. It should be noted that although the simulation results presented will be specific to the network considered, it is expected that key findings will be applicable to various compact network designs employing energy storage.

Network Model Description

For the basis of this study a symmetrical DC network architecture, such as that presented within Figure 1, is considered. In this network, two frequency wild generators are connected in parallel through power electronic interfaces

to a common 270V DC bus bar from which all electrical loads are supplied. All loads are modeled as representative passive elements in order to reduce computational overheads and improve simulation efficiency. A bus segregation contactor, which is closed during normal network conditions, can be opened to form two islanded network sections. The gas turbine engine model driving the two generators is currently represented as a speed-stiff system, whereby changes in electrical loading on the generators do not induce changes in rotor speed. Note that some passive elements such as cable impedances and filter capacitors have been purposely excluded from the diagram for illustrative clarity. Additionally, an energy storage system is connected directly to the main bus bar via a bi-directional converter interface (details of this ESS model are provided in the following section). Protection device models are not included within this network such that its uninhibited fault response may be investigated.

Energy Storage System

The ESS considered for this study is a supercapacitor energy storage device interfaced to the primary bus bar via a bidirectional DC-DC converter, which enables energy absorption/extraction from the network. The system includes a detailed switch level model [16] with a corresponding control system enabling harmonic effects and the ESS's contribution to fault currents to be accurately captured.

The ESS control system, shown in Figure 2, is based upon [17] where the converter output, I_{bus} , is controlled via cascaded voltage and current PI controllers. It is designed to have a bandwidth an order of magnitude greater than that of the generator regulators such that the ESS responds more rapidly to voltage transients caused by changes in load. The primary function of the control system is designed to operate on the network voltage such that the current controller follows a varying reference value, I_{bus}^* , set by the voltage controller, which typically functions to track a constant voltage reference. Additional secondary control algorithms, such as power balance and state of charge control, may be superimposed onto the current regulation to improve ESS performance as in [14]. Note that the additional compensator is included to counterbalance the nonlinear relationship between the output current and modulation index.

Given that the network voltage is normally regulated by the generator droop controllers, the output of the ESS is typically zero when tracking the steady state network voltage. During voltage transient events, normally instigated by a disturbance or change in load, the current controller input reference will adjust accordingly and trigger a change in converter output. As the network voltage settles, the demanded current will decay to zero.

In accordance to the design requirements for the ESS, the converter must therefore be capable of supplying significant current to dampen the transient effects of load variation on the network. However, this high power-dense converter design characteristic together with its control system is