

Impact of Converter Interface Type on the Protection Requirements for DC Aircraft Power Systems

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ABSTRACT

The utilization of converter interfaces has the potential to significantly alter the protection system design requirements in future aircraft platforms. However, the impact these converters will have can vary widely, depending on the topology of converter, its filter requirements and its control strategy. This means that the precise impact on the network fault response is often difficult to quantify. Through the analysis of example converter topologies and literature on the protection of DC networks, this paper tackles this problem by identifying key design characteristics of converters which influence their fault response. Using this information, the converters are classified based on their general fault characteristics, enabling potential protection issues and solutions to be readily identified. Finally, the paper discusses the potential for system level design benefits through the optimisation of converter topology and protection system design.

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INTRODUCTION

The development of more-electric concepts has increasingly seen aircraft designs employ power electronic converter systems for power conversion and conditioning as well as utilizing DC power distribution networks in order to capitalize on efficiency, flexibility and power density benefits [1, 2, 3]. The converter interfaces utilized within these networks can have a significant influence on the fault response of these networks and hence standard approaches to the protection must change in order to accommodate these differences. This influence can vary widely, depending on the topology of converter, its filter requirements and its control strategy and examples of this will be shown in later sections of the paper. As such, the precise impact converters have on the fault response of these networks is often difficult to quantify. This lack of consistency introduces added complexity into the design of effective protection systems and reduces the transferability of a particular protection system design when applied to other networks. The ultimate effect of this is to increase overall system design time, as unique protection solutions must be developed in order to overcome the challenges associated with the integration of new converter technologies into a network.

This paper aims to simplify this design problem by distinguishing different converter topologies based on their general fault response. There are two key behavioral components which influence a converter's response to

network fault conditions; first, the extent of the converter's fault current limiting capability and second, the filter requirements of the converter (and hence the natural response of its passive components to a fault). As the work is set in the context of a DC system, the size of the capacitive filters is specifically considered as these have been identified as a source of potentially significant fault current [4, 5, 6]. The following sections will first review some standard converter topologies, highlighting how different aspects of their design can alter their fault response. The protection system challenges for the different converter types are then discussed.

The paper concludes by describing the two key objectives of this work, which the paper moves towards. The first is the consideration of network protection at the converter selection stage of the design process. The paper will highlight that, among other benefits, this can ensure consistency of protection requirements across the network, leading to more effective network protection. The second objective is the development of transferable protection approaches for future aircraft networks, inclusive of the different converter types. Potential solutions to achieve this goal are identified within later sections of the paper.

REVIEW OF ACTIVE CONVERTER TOPOLOGIES AND TYPES

In order to establish the different categories of converter which may be utilized within DC networks, this section considers the response of converters at a functional level. It is beyond the scope of the paper to perform a detailed analysis of a specific converter fault response, particularly given the massive number of converter topology options which exist. The intention is rather to draw out the key characteristics of a converter's design which impact its response under network fault conditions, from which any potential protection system issues can be inferred. For this purpose, this section first analyses example converter topologies and control strategies to assess their effect on fault response. Specific categories for converter type are then defined.

Six-Switch Voltage Source Converters

The six-switch topology is relatively standard for a Voltage Source Converter (VSC) and this is the topology adopted within much of the literature for DC networks, examples of which are shown in [4, 7, 8], although it is more limited to use in motor drives within aerospace applications at present [9]. The topology consists of six turn off switches (which are often IGBTs), with antiparallel diodes connected across each of the switches, and a capacitive output filter, as illustrated within Figure 1.

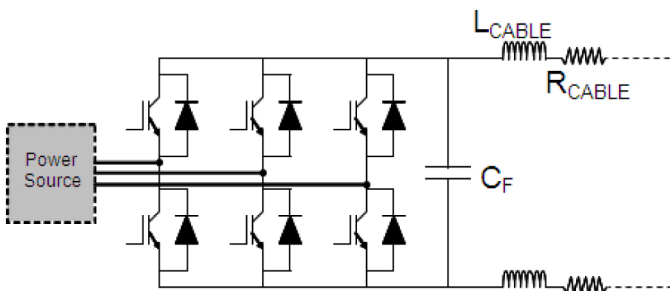


Figure 1. Standard six switch VSC converter

The topology of the six switch VSC converter is such that significant capacitance is often required to achieve sufficient levels of power quality [7, 10]. This capacitance, C_F within Figure 1, is also required to provide a back-biasing voltage across the antiparallel diodes to prevent conduction under normal operation. However, under DC network fault conditions, this voltage may be lost. Under these conditions, the diodes would begin to conduct and the converter would be unable to block the flow of current to the fault [8, 10].

This situation occurs when voltage on the non-network side exceeds the network voltage by more than the diode switch-on voltage. This is illustrated in the simplified circuit in Figure 2.

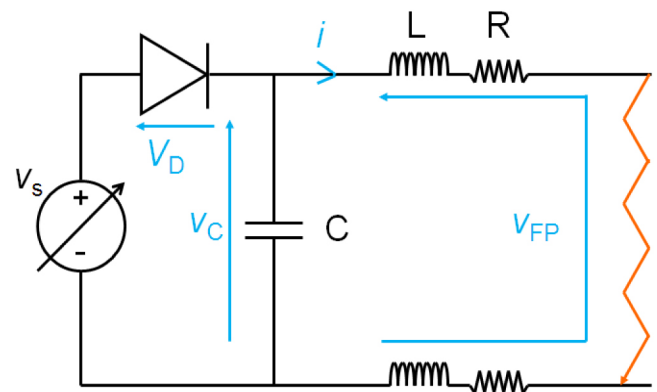


Figure 2. Simplified circuit highlighting the antiparallel diode conduction path and back biasing voltages

From Figure 2, the fault conditions under which diode conduction occurs are

$$Z_{FP} \times I_{CONV} \leq V_s + V_D \quad (1)$$

where Z_{FP} is the impedance of the fault path (including the line and fault), I_{CONV} is the converter output current and V_D is the on-state voltage of the antiparallel diodes in the converter. Equation (1) highlights that the level at which the converter can continue to control current is highly dependent on the impedance of the fault path. For compact aircraft systems with relatively low voltage drops on the conductors, it is clear that this control would be lost in the majority of fault conditions, and would only be retained where the fault itself had reasonably large impedance. This is particularly problematic as the fault current withstand of VSCs is low compared to more robust thyristor based converter topologies [4, 7], therefore current must be limited or interrupted much more quickly to prevent damage to internal components when supplying fault current. These types of issues are discussed in more detail within later sections.

Two Switch Buck-Boost DC/DC Converter

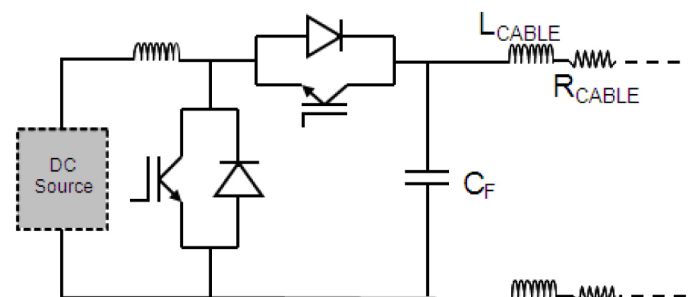


Figure 3. Two switch buck-boost DC/DC converter topology [11, 12]

Figure 3 illustrates the topology of the conventional two switch buck-boost DC/DC converter, a converter which has been proposed for use to interface energy storage elements to a DC network in electric vehicle and aerospace applications [11, 12]. This type of converter has similar characteristics to that of the VSC, requiring large filter capacitance (which can be prohibitively large in some cases [13]) and containing antiparallel diodes. As with the VSC, the location of these antiparallel diodes means that if output voltage was lost, the diodes would conduct current. As the converter switching elements would be bypassed, it could no longer control current magnitude.

Interleaved DC/DC Converter

The design of the interleaved DC/DC converter has evolved from the conventional two switch converter and enables a reduction in converter size and an increase in efficiency and reliability [13]. An example the interleaved DC/DC converter topology is illustrated in Figure 4.

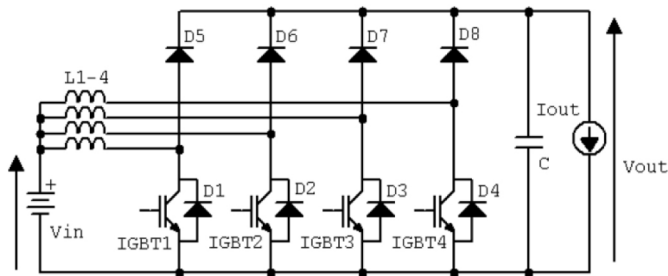


Figure 4. Interleaved 4-channel boost DC/DC converter [14]

The key benefits of the interleaved design are derived from the converter's parallel switches and coupled inductors, which reduce the burden on the capacitive output filter, enabling a reduction in its size. The extent to which these filtering requirements can be reduced is partly dependent on the number of parallel channels utilized as an increase the number of channels will decrease output voltage ripple [14]. The performance improvement through the use of an interleaved topology does however come at the cost of additional inductors and power switching devices [13]. Furthermore, the location of the diodes within this converter topology is such that they would be unable to block current during loss of DC side voltage, as with the previous converter types.

Crowbarring

One means of limiting current output when antiparallel diodes exist within the converter is to utilize a crowbar. A crowbar can be applied by either activating a physical crowbar on the source side [15] or by turning on the active switches within a leg of the converter to create an internal crowbar [16], effectively providing the converter will current limiting capability. The degree to which the crowbar could limit fault current would depend on the impedance of the

crowbar itself and that of the fault path. Application of a crowbar would likely lead a scenario where current is split between the crowbar and the fault. In any case, it is essential that the crowbar is capable of handling high currents for a sustained period, which may require the use of highly rated switches [16]. This requirement also applies to the source, which would be required to sustain an effective short circuit across its terminals without causing itself damage.

Antiparallel Diode Replacement

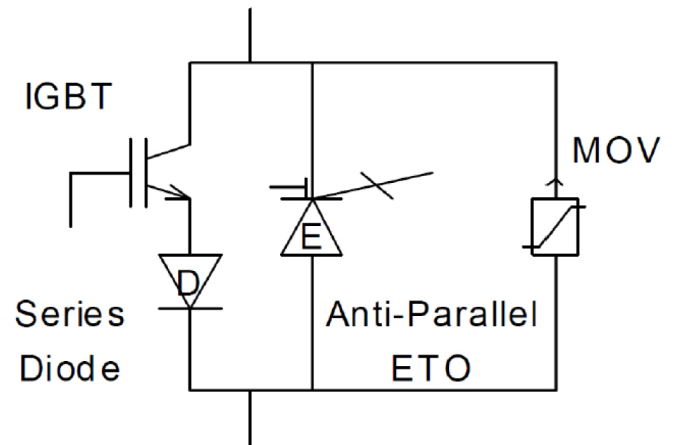


Figure 5. VSC switch Realization with IGBT and Anti-Parallel ETO Device [17]

Figure 5 illustrates a modified version of a single switch segment of the standard VSC design, proposed for use within [17]. The design has been modified to replace the antiparallel diode with a turn-off device; in this case an emitter turn-off (ETO) device has been selected, the design of which is described in [18]. In addition to this, a metal-oxide varistor (MOV) has been connected in parallel to suppress voltage transients across the converter during switching events. The primary purpose of replacing the antiparallel diode is to prevent the constant conduction of these diodes following the loss of the back-biasing DC voltage, with the usually turned on ETO giving the converter the capability to limit or interrupt current, albeit at the cost of increased conduction loss in the antiparallel diode path. As the capacitive filter is located on the DC side of the converter, the discharge phase the fault response remains, however the topology change enables control of the secondary fault infeed from the AC side.

Whilst this topology would add some cost and complexity to the converter design compared to the standard VSC, it does serve as an example of how a converter can be used to limit current into a faulted DC network.

Multilevel and Modular Multilevel Converter Topologies

The application or proposed application of multilevel converters has so far tended towards medium or high voltage