

Composite AC-to-DC Power Converters for More Electric Architectures

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ABSTRACT

This paper presents a novel method and system for an electric power alternating-current (AC)-to-direct-current (DC) converter employing composite technology. The term composite entails utilization of more than one type of conversion operating in parallel. In addition, background information for the prior art, based on conventional autotransformer rectifier units (ATRU), and active converters are discussed. The major requirements of AC-to-DC converters from both functional and protection perspectives are provided. The concept of the new approach is defined. Comparative analysis between the new and old methods is documented. The performance features and technical details of the system parameters with respect to AC-to-DC converter system requirements are presented and discussed. Analysis, simulation results, and test data are included. Finally, the advantages of this technology, which nearly doubles power density compared to the state-of-the-art, are summarized and a conclusion included.

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BACKGROUND

Aerospace Trends in AC-to-DC Power Conversion

The more electric architecture (MEA) initiatives continue to be a dominating trend in the aerospace industry, as they have for the last two decades. The commercial aircraft business is moving toward no-bleed-air environmental control systems (ECS), variable-frequency (VF) and DC power distribution buses, and electrical actuation. A typical example is the Boeing 787 platform. The next-generation Boeing and Airbus narrow-body airplanes will most likely use MEA. Some military aircraft already utilize MEA for both primary and secondary flight controls. Substantial progress has recently been made in replacing hydraulic and pneumatic systems with electric ones.

These new aerospace and military trends have significantly increased electrical power-generation needs. The overall result has been a significant increase in the challenges faced when accommodating electrical equipment to the new platforms. This has led to increased operating voltages, as well as efforts to reduce system losses, weight, and volume. A new set of electrical power quality and electromagnetic interference (EMI) requirements has been created to satisfy system quality and performance. The latest tendency as a part of MEA is the energy-optimized aircraft (EOA) in which electric power and heat management are interrelated. Reference 1 provides a top-level point of view for the goal of an EOA, as well as guidance for measurement of the level of optimization. Reference 2 deals with the optimization of the power and

thermal management system (PTMS) for future aircraft, which will be based on high levels of integration and adaptability of the system at different conditions. An interesting discussion on the subject is provided in Reference 3 where the electronics is reviewed in the context of the power plant. The conclusion is that the power electronics appears to be the most difficult issue to master and must be considered from various aspects. Overall system performance improvement, especially power density increases are necessary for the new-generation hardware. This is particularly so for the AC-to-DC power conversion, which is a substantial contributor to the weight, volume, and cost of the power electronics.

Major Requirements of an AC-to-DC Power Converter

Power quality is a major concern for MEA aircraft because a large number of electric power systems and a large amount of equipment are installed on the same bus. The power quality of these systems and this equipment has much more stringent requirements to ensure that all power supplies and utilization equipment function together properly. Reference 4 presents analysis results of a Boeing effort to address power quality requirements due to changes in power system architecture and changing technology load equipment, including power electronics, motor controllers, and large dynamic loads. Transient analysis and stability aspects are addressed in Reference 5 by exploring different methodologies. A systematic method has been developed in Reference 6 to model small-signal input behavior of multi-pulse rectifiers for MEA system stability and power quality analysis. The developed input

impedance models are given in analytical forms and do not need to be re-derived when the load changes. The method can be applied to different transformer rectifier units (TRUs) and ATRU circuits.

For power supply equipment, additional monitoring features are implemented to detect and isolate equipment, or groups of equipment, that could experience a power quality issue. This isolation capability is to protect the other operating power supplies and utilization equipment.

For power utilization equipment, strict power quality requirements are imposed. Some reasons for the requirements are as follows:

- Equipment contributing to power quality problems causes other equipment to fail.
- Equipment is prevented from achieving its design performance or reliability due to the reduced power quality of the source.
- Perhaps to meet a desired minimum weight, equipment designed with no power margin tends to be more susceptible to power quality issues. Also, equipment designed to minimize weight tends to create power quality issues.
- Equipment can fail due to self-generated power quality problems.

Power quality requirements for AC electrical equipment consist of a large number of parameters such as: current distortion, inrush current, voltage distortion, voltage modulation, power factor, phase balance and DC content.

Current distortions composed of AC harmonics are the key design drivers for equipment. The requirements for current harmonics, subharmonics, and interharmonics specify the allowable distortion as a function of multiples of the fundamental frequency of the input voltage.

A typical current harmonic requirement includes all odd harmonics up to 39, with limits ranging from 10 to 0.25 percent of the maximum current fundamental. The current distortion requirement is a key design driver since it usually significantly impacts the equipment weight.

Current distortion also is specified as a function of the equipment-rated power because the higher power equipment has more influence on the power bus.

For AC-to-DC converters, the requirements for the DC output are also important. These include ripple voltage and voltage droop. The ripple voltage and voltage droop determine the DC operating range of the output equipment such as inverters. Also step up and step down of the output voltage is an important requirement for some applications. Reference 7 explores two novel 18-pulse topologies with emphasis of leakage reactance sensitivity to obtain power quality

compliance for variable high-frequency operation (360 to 800 Hz). Reference 8 addresses the issue of obtaining step down output voltages of 270 Vdc from 230 Vac of the latest busses. Various architectures have been explored. The conclusion is that for most applications 12-pulse ATRU topologies will satisfy the stringent power quality requirements and, for some applications, 18-pulse systems will be required.

Passive vs. Active AC-to-DC Power Converters

Historically, passive AC-to-DC converters have dominated in the aerospace power electronics industry because of the following reasons: simplicity, lack of stringent power quality requirements in the past, lack of stringent EMI compliance requirements in the past, and no need for regeneration of electric power to the distribution bus.

Various active and passive configurations for a rectification system that minimize the characteristic harmonics of the input phase current waveform and achieve compliance with the harmonic current specifications for future more electric aircraft are presented in Reference 9.

Qualitative rating of different converters is shown. The conclusions are that the passive converters present better reliability and that the active converters may gain momentum in the future with the advancement of the semiconductor industry. Reference 10 and Reference 11 further explore the power quality aspects of the active converters and reiterate the conclusion that the main disadvantage of the active converters is poor reliability.

Active rectifiers have been accepted in commercial applications, but their selection in the aircraft power systems are just in the first phase for small power level only as concluded in Reference 12.

Reference 13 concludes that there are two primary groups of technologies capable of meeting the new power quality requirements: passive and active. In cases where voltage regulation is not critical, passive multi-phase power conversion offers significant advantages in aerospace applications.

The passive AC-to-DC converters usually comprise diodes and filtering capacitors. They present low losses, high reliability, and low weight and volume. The main representative for a three-phase distribution bus is the three-phase diode bridge, which comprises six diodes and one smoothing capacitor in its minimal configuration. The main disadvantages of these converters are the high level of harmonic content in the input currents resulting from the six-step commutation and the inability to transfer power to the opposite direction.

As a part of the MEA initiative, increased-power-level electronics equipment has been installed on the latest platforms. This results in a large quantity of utilization hardware connected to the same distribution bus. Hence, there is a complex relationship between various loads and the power

generation system is created. The mitigation provision is to create well-defined, stringent power quality and EMI compliance requirements. A conventional three-phase bridge does not satisfy the new environment. Complex passive filters must be added for compliance, which leads to a substantial weight penalty.

Power quality improvement has been achieved by implementing various passive schemes with increased steps of commutation: the larger the number of steps, the lower the amplitudes of the input harmonics. Also, some low-frequency harmonics disappear with larger commutation frequency. The high-frequency harmonics are easy to mitigate with smaller inductors and capacitors. To increase the number of commutation steps from 6 to 12, 18 or 24, the three-phase distribution bus is converted to a six- or nine-phase bus and then rectified. A great variety of transformers and autotransformers can be used to perform those tasks. It is believed that 12-pulse converters are lighter than 18-pulse converters. So designed multi-pulse AC-to-DC converters experience increased weight and volume, worse losses, and reduced reliability. However, at this point these solutions look most attractive for medium-to-low-power-level applications when unidirectional power transfer only is required.

The drive for EOA postulates the need for bidirectional power transfer. This creates an opportunity to reuse the regenerated power coming from some loads like electrical actuators. Active rectification has come onboard to satisfy this complex task. The most common active rectifier is a three-phase bridge that comprises six diodes, six switching devices, a DC link capacitor, and three interface inductors, for decoupling with the distribution bus. To implement proper high-performance operation, sophisticated digital vector control algorithms are required. This leads to use of additional DSP-based control electronics with a gate driver for each switching device. Power quality compliance is relatively easy due to controllability of the input currents wave shape. EMI compliance is probably more difficult due to differential and common mode noises coming from the switching devices. Quite competitive AC-to-DC converters with bidirectional capability can be obtained. However, reliability is drastically reduced due to the increased number of components and the connections between them. There is a great variety of active rectifiers with different characteristics. Their success is application driven. In addition, some AC-to-DC active converters are not bidirectional, e.g., Vienna rectifiers.

It is believed that in power levels above 25 KVA, active rectification is the winner from a weight and volume perspective. Consequently, if there is no need for bidirectional operation and the power levels are below certain levels, the passive multi-pulse rectification is the preferred option.

COMPOSITE AC-TO-DC CONVERTER

Concept Definition of an Idealized Converter

The term “composite AC-to-DC converter” has been coined to distinguish a converter using two or more conversion methods in parallel. [Figure 1](#) is a top-level block diagram of a composite converter. The main rectifier is a three-phase, six diode conventional rectifier operating in parallel with a supplemental rectifier. The supplemental rectifier can be realized as an active rectifier or as a passive rectifier utilizing transformer or autotransformer and diodes. It appears that a multiphase ATRU is the most promising option from the perspective of input harmonic performance. The important function of the main rectifier is to convert AC power to DC power with very competitive weight and volume. The input current of such a device presents wave shapes that are nearly rectangular as can be seen in [Figure 2](#). Hence, it is creating a very disturbed harmonic content at the power distribution bus as seen in [Figure 3](#). The main function of the supplemental converter is to convert power to supplement the input current of the main rectifier so that the total input current of both rectifiers results in an ideal sinusoidal wave shape. To accomplish such a task, the supplemental input current needs to have a quite complex wave shape with a rich harmonic content. The result in this idealized case is that the total input current does not present any harmonics. The AC filter at the power distribution bus provides electromagnetic compliance (EMC). The C is a DC link capacitor to smooth the output voltage.

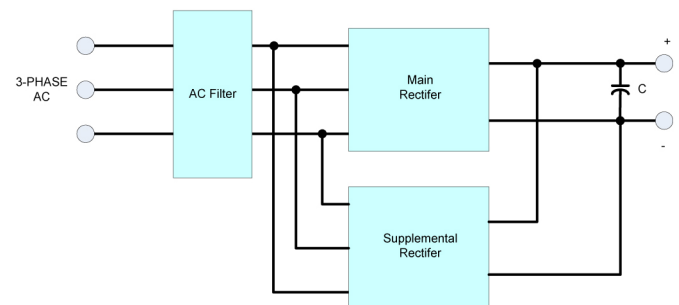


Figure 1. Composite AC-to-DC converter block diagram

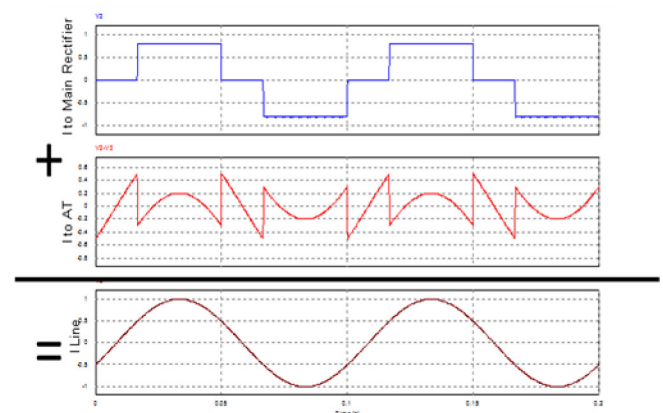


Figure 2. Composite AC-to-DC converter timing diagram - ideal case