

Aircraft Electrical Power Systems and Nonlinear Dynamic Loads

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ABSTRACT

Aircraft utilize electrical power for many functions ranging from simple devices such as resistive heaters to highly advanced and complex systems responsible for communications, situational awareness, electronic warfare and fly-by-wire flight controls. The operational states of these electronic systems affect safety, mission success and the overall economic expense of operation and maintenance. These electronic systems rely on electrical power within established limits of power quality.

In recent years, electrical power quality is becoming excessively degraded due to increased usage of nonlinear and dynamic loads coupled to aircraft power systems that were neither designed nor tested for these loads.

Legacy power generation systems were designed for electrical loads with resistive and inductive properties, which previously represented the majority of actual aircraft electrical loads. As more complex and advanced electronic systems were invented, mostly due to developments in semiconductors, the characteristics of electrical load signatures evolved and transitioned from mostly linear to a dominant nonlinear and randomly dynamic composition. This transition to predominantly nonlinear loads is primarily due to the fundamental processing techniques of electrical power from its original state (i.e. AC/DC source) to the various required intermediate and final states of power in order to accomplish the tasks required of the electronic systems.

Switch Mode Power Supplies (SMPs) and other rectifying circuits using SCRs and diodes, are commonly used on the inputs to avionics equipment, creating the nonlinear loads that adversely affect the power system's power quality. The adverse effects can reduce reliability and degrade the electronic systems resulting in various degrees of faults.

Understanding cause and effect relationships of the dominant nonlinear and dynamic loads on aircraft electrical power systems is the purposes of this paper. Actual test data of military aircraft power systems exhibiting these conditions is presented here to make the reader aware of the problem and provide a relative basis for comparison. An analytical model is used to replicate the issues and show how simulations can aid engineers with determining the effects on their systems without performing costly and possibly destructive tests on actual equipment. These efforts support future activities such as revision of standards for aircraft electrical power systems and ultimately how they are designed, tested and utilized in a more severe and complex environment.

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INTRODUCTION

Aircraft electrical power systems have been used since 1913 for radio communication, navigation and lights [1]. In the beginning, the electrical power supplies on the aircraft were rather simple direct current (DC) systems and provided

power for a few lights, motors, radios and engine starter battery charging. As aircraft became larger and more complex, higher-voltage 400 Hz AC power was introduced to meet the demand for more electrical power. Operation at a higher voltage resulted in much smaller, lighter-weight power wiring when compared to heavy, low-voltage (12/24v) DC



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power wiring. Relatively lightweight transformers converted 115 volts AC to low-voltage DC at a low cost. The AC loads were still linear because they mostly consisted of incandescent lights, motors, resistive heaters, fans, and a few low-power radios. A linear load is a load in which a small increase in applied voltage creates a proportional increase in current.

The semiconductor and electronics revolution enabled aircraft capabilities that aircraft and power systems designers had never fathomed. These devices included electronic flight controls, digital displays, and larger radars. The availability of efficient, high voltage switching transistors and custom integrated circuit switching mode power regulator chips enabled high to low DC voltage conversion for the embedded micro computers that made these advanced devices possible. The classic high-efficiency switch mode power supply (SMPS) is constructed with a full-wave bridge rectifier charging a large input filter capacitor which draws very high-amplitude, short time duration current pulses near the peak voltage of the aircraft's AC power sine wave. This current pulse causes flat-topping and distortion of AC waveform. This current pulse can be approximated by the function $(\sin x)/x$ and introduces predominately odd harmonics of the 400 Hz power frequency. This brief, high-current pulse is a classic nonlinear load to aircraft generators. Nonlinear loads either draw less current with increasing voltage, draw high current surges near the peak voltage, or generate harmonics that are fed back into the power generation equipment and power bus. A switch mode power supply is, by nature, a constant power load. As the input voltage to the switching mode power supply increases the input current decreases. This negative impedance load is a nonlinear effect.

The size and weight of a power transformer is approximately inversely proportional to its frequency of operation for a constant amount of power transferred [2]. For example, a power transformer in a 40 kHz switch mode power supply is a small fraction of the size and weight of a 400 Hz transformer. The conducted emissions from multi-kilohertz switch mode power supplies are controlled to allow sensitive receiving equipment to operate properly. Consequently electromagnetic interference (EMI) filters are used on the power input wiring into the switch mode power converter electronics box. These EMI filters use inductive and capacitive elements to filter power converters' switching frequency and harmonics from being conducted back into the input power wiring and being radiated throughout the aircraft. High frequency EMI filters are smaller than low frequency filters for a constant power and attenuation, similar to the relationship between frequency and size for transformers. A small, high frequency EMI filter can do nothing for the harmonics that are generated by the converter's input full wave bridge rectifier diodes and input filter capacitors that distort the 400 Hz power waveform. These harmonics are primarily 3rd, 5th, 7th and 9th harmonics of a 400 Hz waveform. The size, cost and weight of an EMI filter to block the 3rd harmonic (1200 Hz) of 400 Hz is 33 times larger

compared to a 40 kHz filter. Thus, it is important to analyze the causes of these harmonics in order to find an effective, size- and weight- efficient solution to the distortion.

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Causes for power quality conditions that exceed specified limits are related to the interactions of a finite power and distribution system and a nonlinear dynamic loading environment [3]. Voltage and current provided at the point of load by the power system are continuously fluctuating [4]. The elements within the system that participate in this effect are the engine, transmission, AC generator, DC power converters, inverters, transmission lines, contactors, circuit breakers and utilization equipment.

AC generators will produce voltage as specified in MIL-PRF-21480 for 400Hz systems or in MIL-E-23001 for variable-speed, constant frequency systems when subjected to simulated linear aircraft electrical loads. However, actual aircraft electrical loads do not resemble purely linear loads. The following reasons describe the various causes for power quality disturbances on AC buses.

- Power supplies. Passive types such as transformer-rectifiers (6, 12, and 18 pulse) can cause voltage and current harmonics, unity or leading power factor, generator loading, and generator control issues. Switch mode power supplies can also produce these effects. In addition, they can draw a short-duration high-peak current, lowering the sine wave voltage peak.
- EMI filters. EMI filters typically cause higher overall load capacitance, large current inrushes and large voltage transients upon start-up.
- Pulsing loads. Presently there are no requirements in generator specifications to provide power to pulsing loads. The effects of the pulsing loads include voltage and frequency modulation and transients. If these pulsing loads pulse at a rate near the resonant frequency of the generator and its mechanical drive system, they will cause shaft, bearing and gear failures.
- Motor loads. In general, there are no motor load requirements for generators. Motor loads can create voltage and frequency transients on aircraft electrical power systems.
- Grounding. Grounding has been neglected in many aircraft designs because of the excellent ground provided by the aluminum structure as well as the low amount of current returned through the structure. Advancement in composite aircraft structure along with the ever increasing electrical load requirements of modern aircraft present new challenges for aircraft grounding systems. These advancements in aircraft design will result in a number of grounding issues such as structure heating, corrosion, increased voltage drops and increased signal noise coupling to sensitive circuits. In addition, short-circuit protection performance is affected

since a higher ground impedance can cause circuit breakers to take a longer time to trip.

Some of the results of these issues can be seen on aircraft. **Figure 1** below shows a typical 60 kVA, 115 Volt, 400 Hz, 3-Phase AC generator voltage and current exhibiting a smooth sine wave under full-load 1.0 power factor linear load.

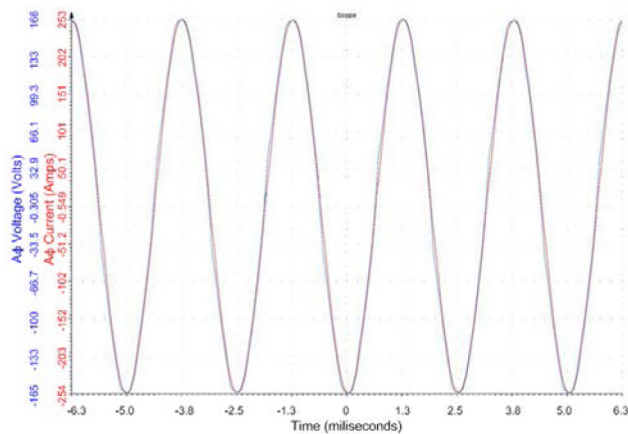


Figure 1. AC generator with linear load.

The effects of nonlinear loading are apparent in **Figure 2**, which shows the distorted sine wave of the same AC generator under 30% non-linear load conditions. Under this condition, the generator is required to produce additional current for the nonlinear loads due to the generated harmonics. This produces more heat inside the generator and the resulting stress on the generator reduces its maximum lifetime.

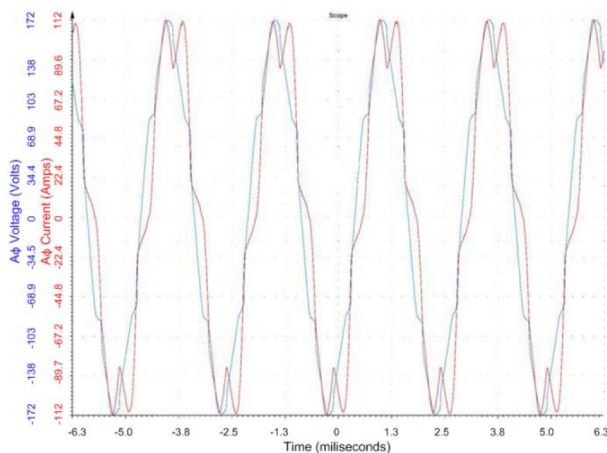


Figure 2. AC generator with nonlinear load.

Primary and main system DC power supplies for aircraft vary in design and are controlled by well established standards such as MIL-C-7115 for AC to DC converters and MIL-DTL-6162 for DC generators [5]. These converters and generators are necessary to provide conditioned and stabilized power to various electronic systems with reliability

as a primary requirement. Additionally, the quality of the power while operating in every possible condition must remain within limits that permit electronic systems to operate continuously and without fault or any degradation [6]. Certain conditions can occur that result in faults or degraded performance of electronic systems when power quality characteristics are well within the limits specified in these standards. One example is excessive radio frequency noise caused by the ripple current produced by the normally operating DC sources (generators or converters).

Another example of distortion caused by non-linear loadings is shown in **Figure 3**. The voltage and current outputs of a 400A, 30V DC generator are under 160A linear load conditions. Voltage and current ripple are at 1.7V and 19A, respectively.

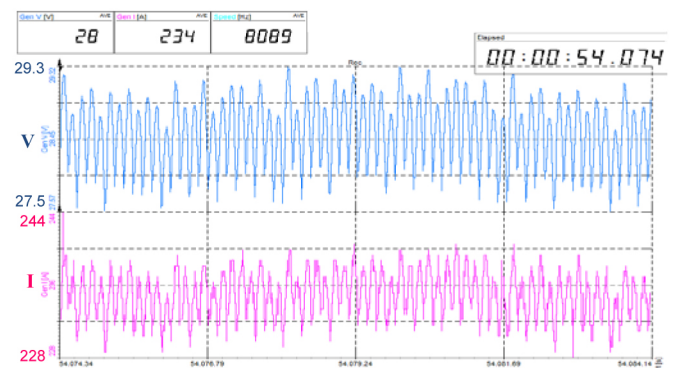


Figure 3. DC generator with linear load.

With the same generator placed under 130A linear and 190A nonlinear load (**Figure 4**), voltage ripple increases to 2.9V and current ripple increases to 109A.

When the load is pulsed on and off (**Figure 5**) the voltage and current ripples increase to 8V and 216A, respectively.

Causes for power quality disturbances on the DC bus are related to several conditions that may act separately or simultaneously on the AC and DC buses. Some effects are caused by the various topologies of AC to DC power conversion processes and certain types of DC loads. These loads vary between linear and nonlinear with dynamic characteristics (i.e. pulsed loads). The various amplitudes and frequencies of these loads, when combined, exacerbate the disturbances further. Converters with finite output impedances have extremely limited energy storage and a relatively high ripple voltage and cannot provide highly dynamic loads with adequate power quality. The combination of these conditions can result in MIL-STD-704 power quality violations [7].

Furthermore, transient conditions can cause more problems. Two major undesirable conditions that occur are transients and repetitive transients that appear as ripple voltage or voltage modulation. Transient current amplitudes range from several amperes (such as with gas turbine ignition systems that pulse energy to combustor) to high amplitudes that can exceed the full-rated bus current limit (such as with