2012-01-2182
Published 10/22/2012
doi:10.4271/2012-01-2182
saeaero.saejournals.org

Aircraft Electrical Power Systems and Nonlinear Dynamic Loads

Charles Singer, Corinne M. Guernsey and Jason Gousy
Naval Air Systems Command

John DeWitte Cottingham III
Champion Aerospace

John Frerichs
US ARMY

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 (SMPSs) 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.

CITATION: Singer, C., Guernsey, C., Gousy, J., Cottingham III, J. et al., "Aircraft Electrical Power Systems and Nonlinear Dynamic Loads," *SAE Int. J. Aerosp.* 5(2):2012, doi:10.4271/2012-01-2182.

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 power wiring. Relatively lightweight transformers converted115 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 33times 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.

CAUSES

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.

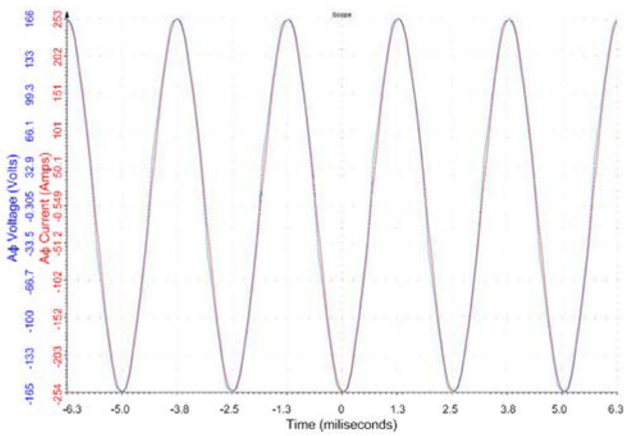

Figure 1. AC generator with linear load.

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.

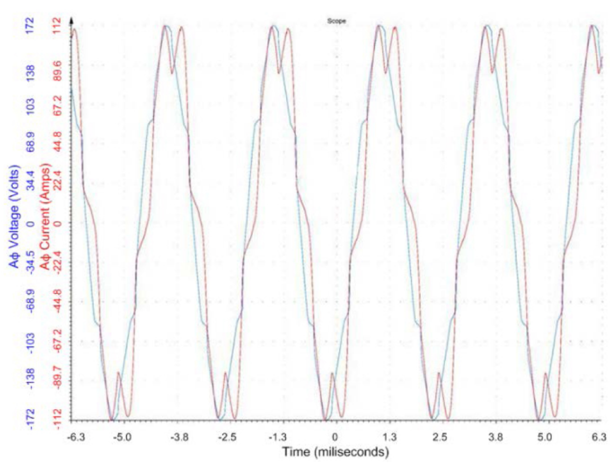

Figure 2. AC generator with nonlinear load.

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.

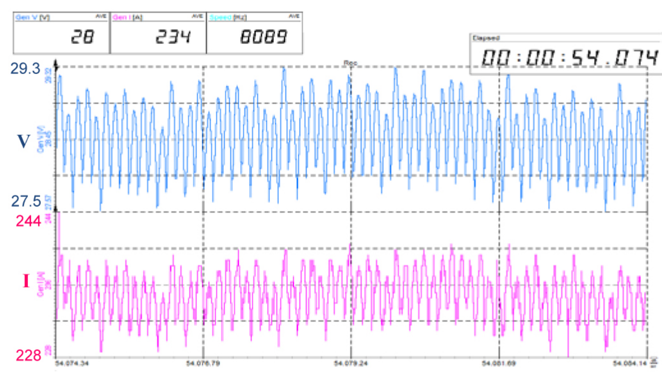

Figure 3. DC generator with linear load.

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 directed energy electronic countermeasures and gun motors). The power quality provided must remain within limits to allow all adjacent systems to operate without faults or degradation. Power source qualification requirements do not specify nonlinear dynamic load performance requirements, which explains to some degree why the power system and utilization equipment can become incompatible. The power system and utilization equipment must operate together without causing adverse effects or disrupting operation.

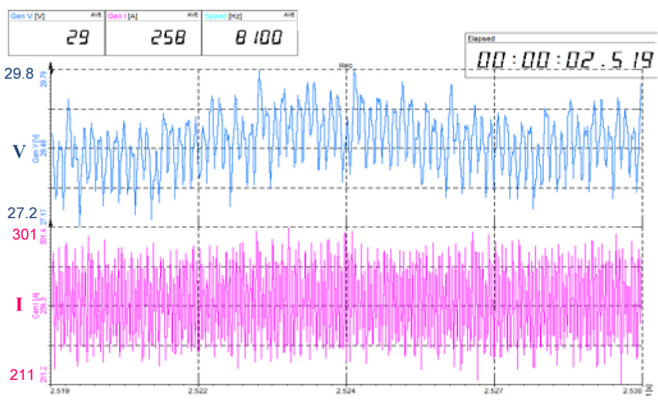

Figure 4. DC generator with 190A nonlinear load.

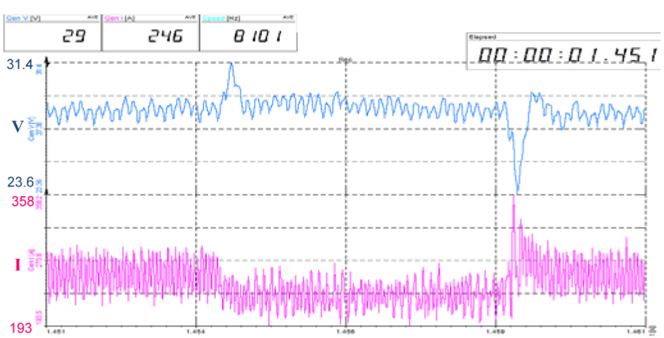

Figure 5. DC generator with pulsing 190A nonlinear load.

A 100VA, 115V, 400Hz single phase inverter is shown in Figure 6 under 100% linear load conditions. The load voltage and currents are exhibit typical smooth sine waves.

The performance of the same inverter placed under 80% non-linear load is shown in Figure 7. More current is required from the power source during the sine wave peaks, which are flattened by the nonlinear loads' current surges, thus decreasing the life of the inverter.

The effects of a 150A Transformer Rectifier Unit (TRU) placed under 88A linear load are shown in Figure 8. Output voltage ripple is 0.78V and current ripple is 2.7A.

The same TRU is placed under 66A linear and 50A nonlinear, pulsing load and the results are shown in Figure 9. Not only are there visible spikes in voltage and current when the load is pulsed on and off, but the voltage and current ripples jump to 5.31V and 39.3A respectively. The demonstrated ripple far-exceeds the MIL-C-7115 limits for output ripple and also exceeds MIL-STD-704 power quality limits.

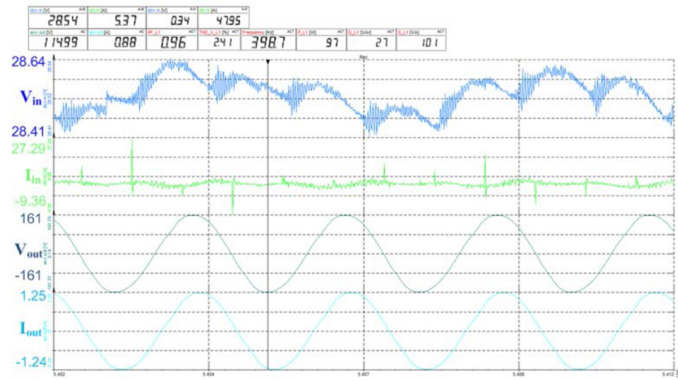

Figure 6. Inverter with linear load.

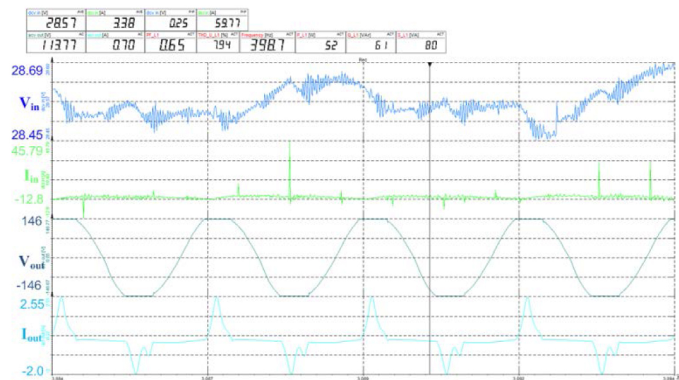

Figure 7. Inverter with nonlinear load.

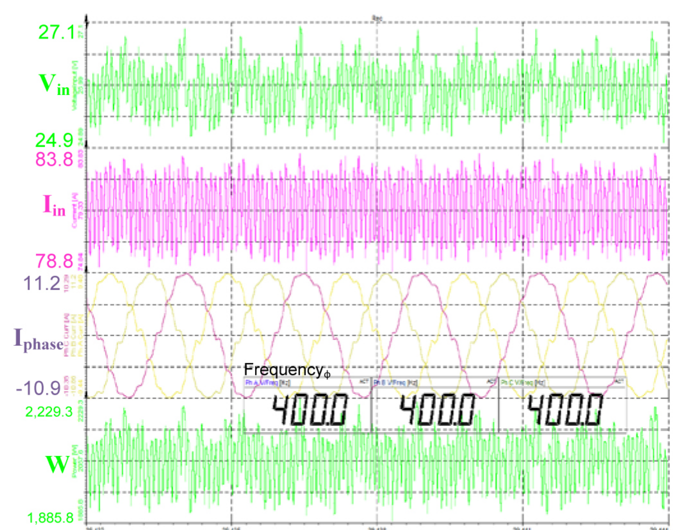

Figure 8. TRU with linear load.

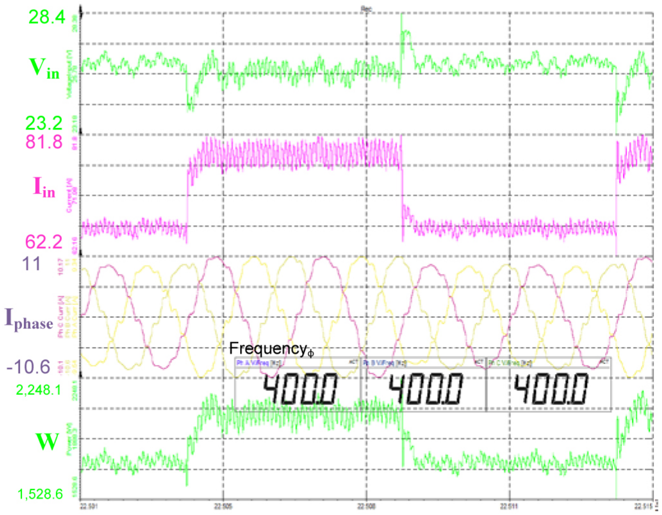

Figure 9. TRU with nonlinear, pulsing load.

Testing electronic systems is generally considered a thorough means for determining compatibility. Finite limits for power quality and EMI emissions are well established in various standards like MIL-STD-704 and MIL-STD-461, but testing for all conditions simultaneously is cost prohibitive and practically impossible. Laboratory, ground, and flight testing identifies and reduces the likelihood of faults but does not completely eliminate the possibility. The solution to these faults can be achieved by increasing design margins between the environmental characteristics of the aircraft electrical power system and utilization equipment [8]. Survivability and susceptibility must be implemented in order to reduce risks and the economic burden of excessive maintenance costs for advanced electronic aircraft systems.

EFFECTS

The effects of low power quality severely affect modern power systems. Switch mode power supplies are now so small, inexpensive and efficient that every electronics box has at least one and many boxes have several. Each power supply has an EMI filter on the input power. Each of these EMI filters adds a capacitive input impedance at 400 Hz. The contribution of one switch mode EMI filter and power supply is small, but in an aircraft with dozens of electronics boxes each containing one or more filters, the aggregate effect is large. The 400 Hz harmonic currents are increasing on aircraft power buses and the AC bus power factor is becoming more and more capacitive from the added EMI filters.

Harmonic distortion caused by nonlinear loads can impact other components in the electrical power system. The input rectifiers and filter capacitors of switch mode power supplies cause harmonic distortion on the power bus. Most aircraft 400Hz power systems are 3-phase Y-connected using the metal airframe as the neutral return conductor to save weight. Ideally, a 3-phase balanced resistive or inductive load will have a zero neutral current. However, if the 3-phase loads generate harmonics, the triplen harmonics (3^{rd},6^{th}, 9^{th}, etc.) will convene in phase in the neutral return. Balanced, highly nonlinear loads that generate triplen harmonics can have neutral currents that are not only non-zero, but can exceed the individual primary phase currents. These currents can generate voltage drops across the airframe, undesired voltage offsets, and noise on other electrical systems that use the airframe as the signal return, like intercoms and sensors. When this happens, components are subject to poor power quality even if they were uncoupled to non-linear loads before.

Negative impedances, such as those caused by SMPSs, also contribute to power quality issues [4]. If enough under-damped inductance is inserted between the SMPS power input and the power source, the SMPS input will oscillate due to the series inductance and the SMPS's negative input impedance [9]. Common “off the shelf” low loss, high quality EMI input filters installed in front of a SMPS will cause the SMPS' input to oscillate resulting in poor performance or damage. This oscillation will also induce sub-harmonic currents into the power bus. All SMPSs must have a proper resistive damper between the power supply input and the EMI filter in order to have a positive impedance [4]. Adding EMI filters to existing electronic boxes to cure system noise problems may be counterproductive unless parallel resistive damping is added to stabilize the input power to the SMPS. A poorly damped EMI filter in an electronics box can cause voltage to oscillate if a few dozen feet of wiring is added to connect the box to the aircraft bus due to the additional inductance of the power input wire. Electronic boxes have failed MIL-STD-461 conducted emissions testing because the inductance of the standard 50μH LISN's (Line Impedance Stabilization Network) and the EMI room filters added enough inductance to destabilize the power supply(s) inside the electronics box under test. Negative input impedance is a problem created by non-linear loads that need to be remedied in order to promote good power quality.

The very nature of an aircraft electrical power system's architecture leaves it vulnerable to power quality fluctuations. The generator and generator regulator form a classic closed loop feedback control system. An AC generator is essentially a rotary amplifier such that more field current generates more output current if the output voltage is constant [9]. The aircraft's AC generator works this way for classic legacy resistive and inductive loads on the generator. However, if the load on the generator is a low power factor capacitive load (highly capacitive) then the field current falls off as each additional capacitive load is added [10]. This is the opposite of what is expected and makes a stable closing of the generator's control loop very difficult since the load current to voltage phase angle can go from −90 degrees to +90 degrees as the load goes from inductive to capacitive. Most legacy generator control regulators, which were never designed for highly capacitive loads, create oscillating output when subject

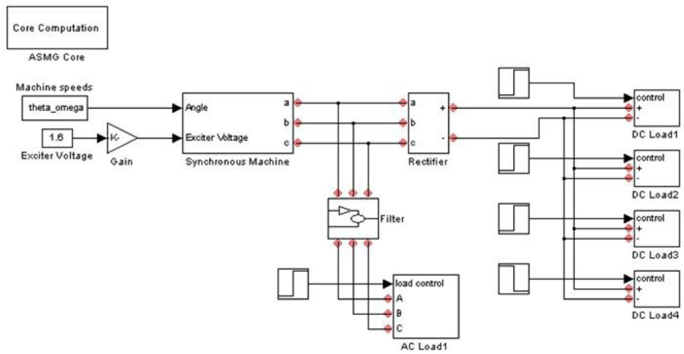

Figure 10. Design of simple generator model with AC and DC loads.

to such loads. This effect looks like modulation of the AC voltage.

MODELING & SIMULATION

Computer modeling can provide the benefit of analyzing potential circuit configurations without the risk of harm to hardware or personnel. The Simulink modeling environment provides a method for simulating the operation of a rapidly switching loads. Such a test using hardware would require a completed circuit, a power supply, safety equipment, and data acquisition devices. While a simple model cannot replicate the actual function of a hardware test, it can provide basic insight into the operation of a device at a fraction of the time and cost.

Before delving into the effect of rapidly switching loads, it is helpful to examine the system using linear, non-switching loads. Shown in Figure 10 is a basic circuit including a 3-phase synchronous machine voltage source, an AC filter, a rectifier, and AC and DC loads. Each of the loads contains a 150Ω resistance, a 1mH inductance and a 1uF capacitance. These loads turn on at various times during the simulation's duration.

The DC loads were replaced with switching DC loads. Figure 11 below shows the DC load voltage with linear loads. The distortion is noticeable when three of the loads switch at 400Hz and a fourth switches at 100Hz, as shown in Figure 12.

Figure 13 below shows the load voltage of the AC load with non-switching loads. The curve is a mostly-smooth sinusoid. The sinusoid shows more distortion when the loads are switched, as shown in Figure 14.

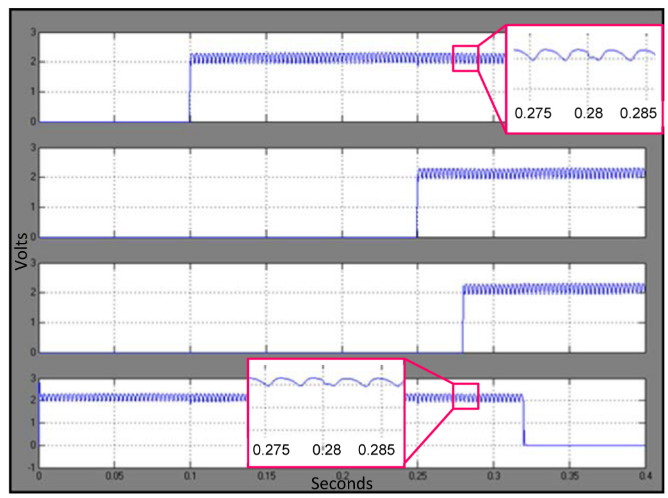

Figure 11. DC load voltage with no switching loads.

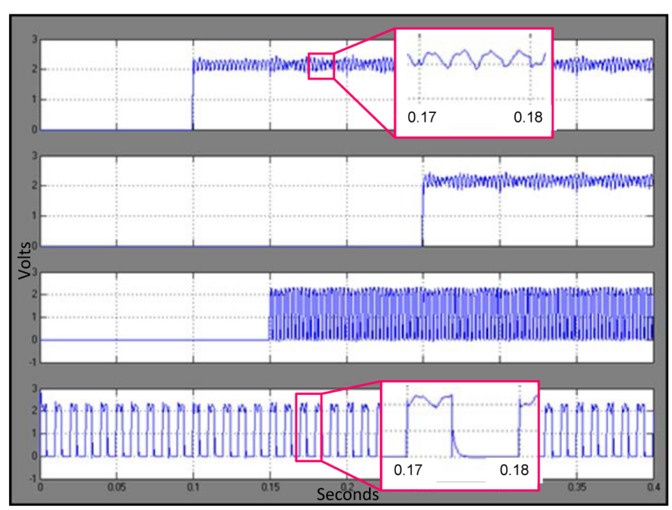

Figure 12. DC load voltage with switching loads.

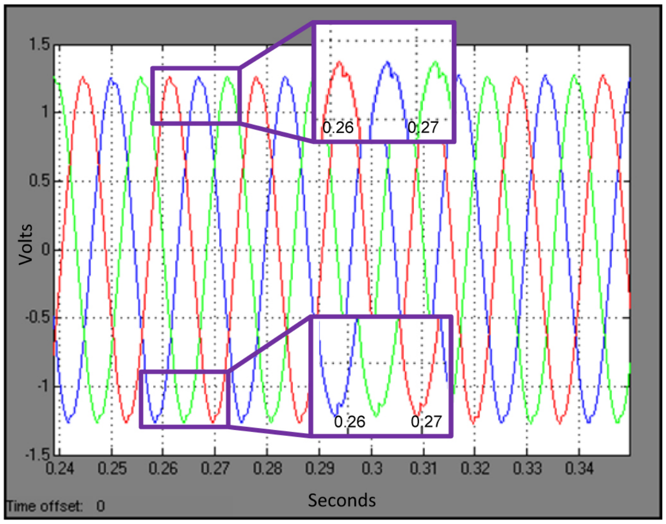

Figure 13. AC load voltage with no switching loads.

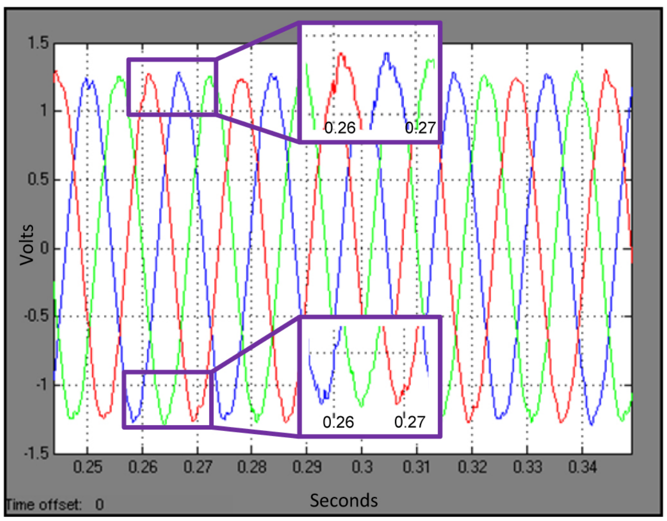

Figure 14. AC load voltage with switching loads.

CONCLUSION

Modern electronic equipment on military aircraft has changed the overall power system load from linear to largely nonlinear in nature. The addition of nonlinear loads such as Switch Mode Power Supplies (SMPSs), EMI filters, pulsing loads and motor loads, coupled with improper grounding has caused issues on the electrical system's sources, which were designed for traditional linear loads. The effects of these nonlinear loads are not well defined or understood and continue to cause power quality degradation as the systems operate outside of equipment design limits. As a result, reliability and overall life of power sources and utilization equipment is surreptitiously degrading.

Testing was performed to determine adverse effects of nonlinear loads on power systems with various aircraft power sources. Nonlinear loads on AC generator systems were found to demand more current than the generator could provide. This demand creates added heat stress on the generator windings and reduces overall generator life. Tests on single phase inverter-supplied systems show simultaneous flattening of the output voltage sine wave and spikes of output current. On DC generator systems, voltage and current ripple increases, causing disturbances on the input to utilization equipment. On DC converter-supplied systems, voltage and current ripple is also increased. When nonlinear loads are pulsed, the ripple increases to outside established power quality limits, degrading the overall reliability of DC system components.

Modeling and simulation of nonlinear loads on power systems can be a useful tool for determining effects on existing systems as well as future applications. However, additional testing of future power sources is needed to determine their ability to provide quality power these nonlinear loads. Power performance specifications will also need to be revised in order to address the new operating conditions. Nonlinear loads will continue to cause problems in aircraft electrical power systems until the aerospace community determines solutions for these new conditions.

REFERENCES

1. Naval Aviation Chronology 1898-1916, http://www.history.navy.mil/branches/avchr1.htm
2. Montsinger, V.M. and Walter, M. Dann, Standard Handbook for Electrical Engineers (Section 6 Transformers Regulators and Reactors), Seventh Edition, McGraw-Hill Book Company, Inc., Maple Press Company, York, PA, 1941.
3. Shengyi, Liu, Singer, Charles H. Singer and Dougal, Roger A., Power Anomaly Effects and Costs in Low-Voltage Mobile Systems, IEEE Transactions on Aerospace and Electronic Systems, Volume 42 pages 612-624 April 2006.
4. Middlebrook, R.D., Design Techniques for Preventing input-Filter Oscillations In Switched-Mode Regulators, Proceedings of the Fifth National Solid-State Power Conversion Conference, Powercon 5 pp A3-1 through A3-16, May 1978.
5. Burdette, A., Goodnow, M., and Singer, C., "An Overview of MIL-STD-704, MIL-HDBK-704, 28 Volt DC Aircraft Utilization Compliance Testing, Electrical Power Quality Causes and Impacts," SAE Technical Paper 2004-01-3156, 2004, doi: 10.4271/2004-01-3156.
6. Mohan, Ned, Undeland, Tore M., Robbins, William P., Power Electronics, Third Edition, John Wiley & Sons, Inc. Hoboken, NJ, 2003.
7. U.S. Navy, "Aircraft Electric Power Characteristics", MIL-STD-704F, March 12, 2004.
8. U.S. Navy, "Guidance for Test Procedures for Demonstration of Utilization Equipment Compliance to Aircraft Electrical Power Characteristics", MIL-HDBK-704, April 9, 2004.
9. MIL-HDBK-241B, Design Guide for Electromagnetic Interference (EMI) Reduction in Power Supplies, 29 November 1984.
10. Electrical Machines II, Indian Institute of Technology Madras, Vasudevan, Krshna, Rao, G., Rao, P., Figure 33, page 47.

CONTACT INFORMATION

Charles H. Singer
US Navy, Electrical Power
Charles.singer@navy.mil

John E. Frerichs
US Army, Mission Equipment Electrical
John.Frerichs@us.army.mil

John DeWitte Cottingham III
Champion Aerospace
WitteCottingham@champaero.com

Corinne M. Guernsey
US Navy, Electrical Power
corinne.guernsey@navy.mil

Jason Gousy
US Navy, Electrical Power
jason.gousy@navy.mil

DEFINITIONS/ABBREVIATIONS

AC - Alternating Current

DC - Direct Current

EMI - Electromagnetic Interference

SCR - Silicon Controlled Rectifier

SMPS - Switch Mode Power Supply

TRU - Transformer Rectifier Unit