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Aircraft DC Power Quality Characteristics of a PCTRU

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ABSTRACT

An overview of aircraft DC power quality specifications reveals that only minor changes have occurred in recent years within industry standards. Current and future advanced electronic aircraft are requiring significant power quality improvements due to increased use of digital and COTS (commercial off the shelf) systems.

Certain electronic systems do not function properly due to various types of electrical disturbances. Some systems shutdown, fault or exhibit operational delays due to power interruptions or “blackout” conditions. Undervoltage or “brownout” conditions also cause this effect. Some electronic systems exhibit critical faults that can affect safety or mission success due to overvoltage conditions. Additional effects of high voltage spikes or overvoltage transients are known to reduce the life of utilization equipment [1], which is directly related to the health of the aircraft’s electronic system and creates an economic burden.

These disturbances are described as high voltage transients, low voltage transients or brownouts, power interruptions and voltage modulation. Another type of perceived perturbation on the DC bus is caused by ripple voltage. All of these are fundamental DC power quality characteristics that can induce problems in electronic systems.

These disturbances are caused by various portions of the entire electrical power system consisting of AC generators, transmission lines, power converters, contactors, electrical power distribution controls and AC/DC loads from utilization equipment.

Presented here is a power supply system described as a Passively Controlled Transformer Rectifier Unit (PCTRU) that preserves the desired reliability of a traditional transformer rectifier unit (TRU) while providing stability to the aircraft 28 VDC bus and mitigating risks caused by these various electrical disturbances.

INTRODUCTION

One major AC to DC power conversion topology utilized for aerospace applications is a simple Transformer Rectifier Unit (i.e. TR or TRU) [2]. These designs represent the most reliable power supply topology, which continually meet the first goal of an aerospace DC electrical power system objective-**reliability**. Significant power quality improvements can be achieved with the basic TRU as described in detail here. However, complex solutions with feedback control (i.e. regulated) topologies that forcefully control power also provide power quality improvements, but these benefits are diminished to an extent by additional failure modes, lower reliability, increased electromagnetic interference for emissions and susceptibility and increased cost. If the DC power supply fails resulting in “loss of power”, power quality is the least concern. Moreover, if the additional fault is “high steady state output voltage”, the more complex solution may cause additional harm to the aircraft electrical system and utilization equipment. These conditions led to the development of a passively controlled power supply that mitigates these risks while preserving reliability.

MAIN SECTION

The typical aircraft DC bus utilizes 28 VDC ranging in current rating for continuous operation from 50 to 400 amperes, with the most common applications requiring 100 to 300 amperes. A common type of power supply is the Transformer Rectifier Unit or TRU, which converts regulated generator power from 115/200 VAC 3 phase 400 Hz to a nominal 28 volts DC for aircraft utilization equipment. Many existing aircraft applications (i.e. fleets) require additional DC power due to increasing loads caused by additional electronic equipment. The range of increased power required for upgraded aircraft programs is typically 20 to 100 percent. Some applications add power supplies incrementally in order to achieve overall system requirements based on a load analysis and testing. Others replace existing power supplies with higher current rated versions due to mounting space limitations.

The DC electrical power quality characteristics discussed here are: voltage regulation (VR), ripple voltage, power interruptions, high voltage transients, low voltage transients and voltage modulation. All of these characteristics are important for new and upgraded aerospace programs for various reasons.

VOLTAGE REGULATION - Voltage regulation or percent voltage regulation, VR, is defined as the ratio of the output voltage change between no load and full load to the full load voltage as a percentage [3]. Voltage regulation of the early traditional TRU was 29 percent at 31-24 VDC. The PCTRU design exhibits an improved voltage regulation of 16 percent at 29-26 VDC, which is nearly 50 percent better than early traditional TRU designs. This improvement eliminates concerns with voltage regulation of the traditional TRU and maintains the same high reliability without involving additional failure modes and overall lower reliability of complex active feedback control topologies (i.e. regulated power supplies).

RIPPLE VOLTAGE - Ripple voltage is defined as the variation of voltage about the steady state DC voltage during steady state electric system operation [4]. This is commonly described as a measure of the power cleanliness for steady state operation. All DC power supplies exhibit ripple voltage caused by the particular conversion process and topology utilized.

Very early TRU designs contained a wye or delta primary and wye secondary resulting in a six-pulse rectification scheme [5]. These devices exhibited a ripple voltage as shown in Figure 1, with this example representing the most severe.

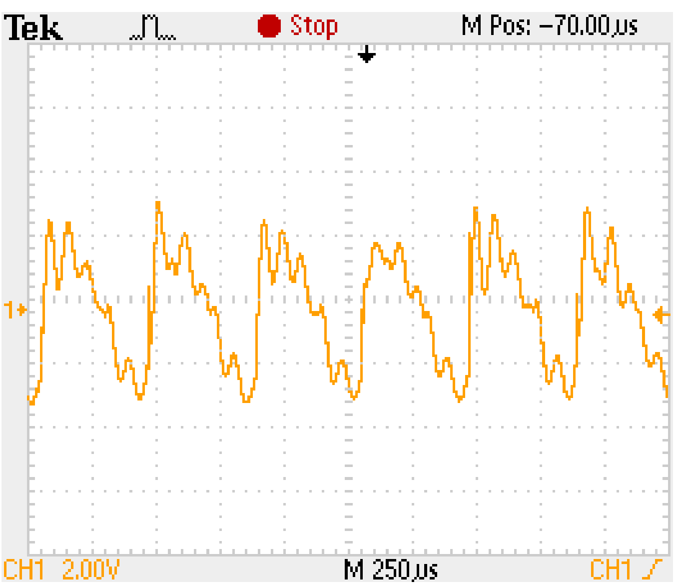

Figure 1: DC Ripple Voltage of Early 6-Pulse TRU

The ripple voltage and harmonic components were greatly improved by use of the wye to delta transformation in the transformer with two six-pulse bridges. This is achieved by a wye or delta primary and a delta-wye secondary causing a 30 degrees phase shift for twelve pulses per revolution of the generator [5], [6]. The result of this topology is a twelve-pulse rectification scheme with a typical ripple voltage shown in Figure 2.

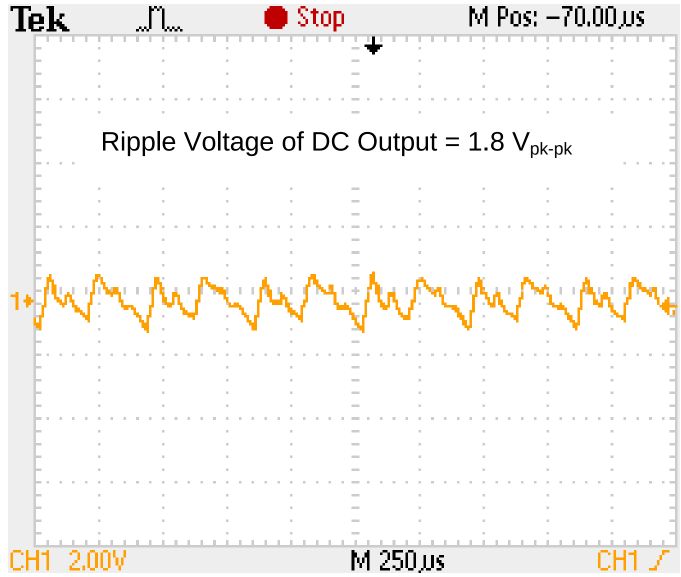

Figure 2: DC Ripple Voltage of a Standard 12-Pulse TRU

This is the foundation of the traditional TRU widely utilized today and exhibits a standard ripple voltage with a balanced input of 1.5-2.0 $V_{pk\text{-}pk}$. Though this complies with ripple specified in MIL-STD-704F of 1.5 V_{pk} maximum amplitude (i.e. 3 $V_{pk\text{-}pk}$), it greatly differs from development and qualification testing conditions of aircraft DC utilization equipment widely used in industry. This difference is due to the common usage of programmable laboratory DC power supplies. Many advanced electronic systems are tested during development and qualification with a programmable DC power supply that exhibits less than 0.2 $V_{pk\text{-}pk}$ (i.e. an order of magnitude better than actual aircraft power). This generates significant concerns with the overall system integration with regards to electronic system faults, compatibility and performance degradations in advanced electronic systems. In other words, a system tested for functional performance, EMI and environmental conditions with a laboratory programmable power supply is expected to operate the same when integrated with many other electronic systems that are all ultimately powered with a much higher ripple voltage (i.e. not as clean) DC power source in the aircraft. Problems in this area can arise and may go unsolved due to “no faults found”, while the system does not operate as qualified or desired. Simple passive techniques in the PCTRU provide a typical ripple voltage of 0.20 $V_{pk\text{-}pk}$ shown in Figure 3, which is a 90-95 percent improvement beyond other aircraft power supplies.

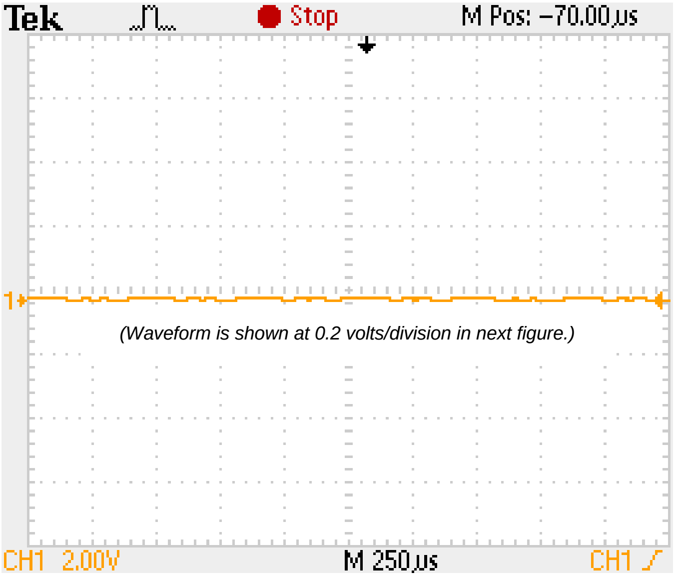

Figure 3: DC Ripple Voltage of a 12-Pulse PCTRU

The ripple voltage of the PCTRU is better viewed with the smaller voltage division as shown in Figure 4 here.

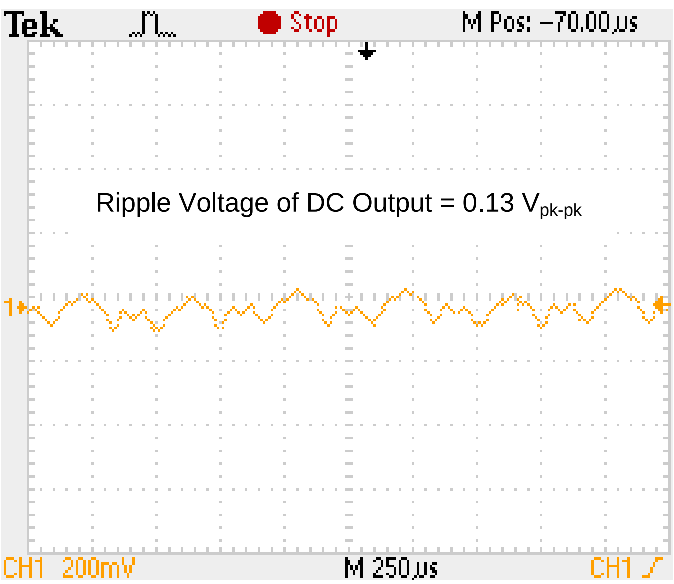

Figure 4: A Closer View of DC Ripple Voltage from the PCTRU

A note to recognize is that "clean" DC power (i.e. low ripple voltage) is independent and unrelated to "voltage regulation" including topologies that contain feedback control; all power supply topologies exhibit ripple voltage, which can be reduced to lower levels with various techniques. This characteristic is mostly dependent on the filter network and power supply topology chosen.

POWER INTERRUPTIONS - A power interruption is defined as a loss of voltage and current from a source to a load for a particular duration of time. Power interruptions are generally unavoidable due to power management and distribution architectures. One of the fundamental components that partly contributes to the power interruption is the "break before make" function of a common type of electrical contactor. This function is a requirement due to potential power generator conflicts that arise if two or more generators are connected together. There are other contributors to power interruptions associated with controls including those used in power system diagnostics.

The maximum time duration of the interruption is generally required to be less than 50 ms [3]. Some aircraft power systems exhibit greater than 50 ms lasting 500 ms or more as shown in Figure 5.

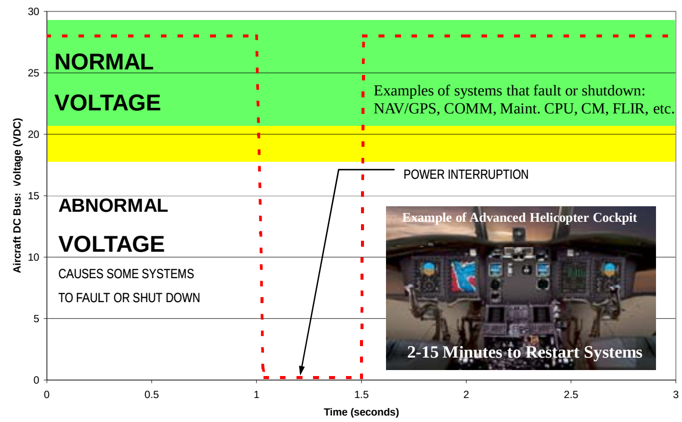

Figure 5: Aircraft DC Bus with Power Interruption

Major computer manufacturers utilize the IEEE Standard 446, "Recommended Practice for Emergency and Standby Power Systems for Industrial and Commercial Applications". It specifies that a momentary undervoltage of 30 percent is acceptable up to 500 ms and a loss of power (i.e. blackout condition) is acceptable for 4-20 ms [2]. This recommended specification is directed towards AC power for computers, but is related to the aircraft electronic system due to "load-based" computer power supplies that reside adjacent to the computer system and initially use aircraft DC power as the source.

The effect of these interruptions cause some utilization equipment to shutdown, fault or exhibit operational delays with less than 50 ms of power interruption. Some of the electronic systems that shutdown can take as much as 2-15 minutes to restart and provide an operational state, which can be unacceptable for mission requirements. These effects range from nuisance conditions to severe where mission safety is jeopardized. The first of two solutions for this situation is to require each manufacturer of the non-compliant subsystem to incorporate additional internal hold-up power. This, unfortunately, is not usually practical due to additional complexities especially when many systems are COTS or would require a redesign and qualification. The second ideal solution is to provide the entire aircraft DC bus with continuous power (i.e. bridge power) during power interruptions. The PCTRU provides bridge power that eliminates normal and abnormal power interruptions in order to maintain a more stable and continuously powered 28 VDC bus. The effect of this is shown in Figure 6.

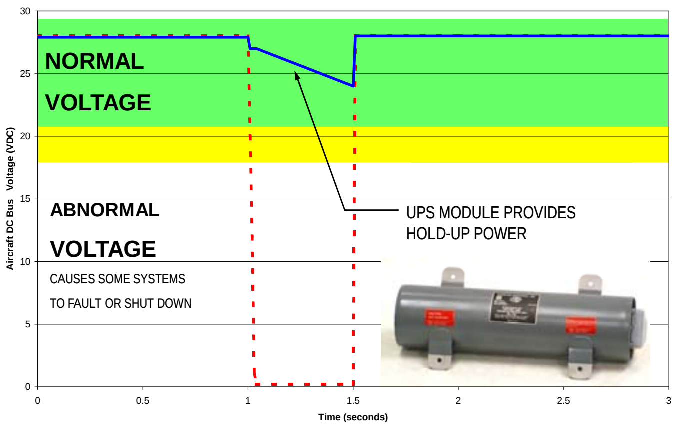

Figure 6: Aircraft DC Bus with Bridge Power from DC Bus Hold-Up Device

The DC Bus Hold-Up device integrated with the PCTRU contains a circuit that automatically charges in approximately 80 seconds and provides bridge power in a passive mode (i.e. normally connected or closed) with a zero time delay. It is capable of providing up to 150 amperes for 50 milliseconds or 80 amperes for 3 seconds during a power interruption in order to maintain an uninterrupted aircraft DC bus. It contains internal sensing circuitry that automatically disconnects its internal hold-up power (i.e. stored energy) from the 28 VDC bus when the main DC power source is removed or turned off for a predetermined time; this primarily accommodates the normal process for an intentional shutdown commanded by the pilot or other personnel. The device also disconnects automatically when the bus voltage is 18 VDC or less. The DC Bus Hold-up device is qualified to Aircraft Electrical Power Characteristics MIL-STD-704A-F.

HIGH AND LOW VOLTAGE TRANSIENTS - High voltage transients are generally understood as “life altering events” for utilization equipment containing semiconductor devices. Utilization equipment containing semiconductors describes nearly all advanced electronic equipment. Degradation of the PN junctions of semiconductor devices is the life reducing effect caused by high voltage transients [1]. Transients range from “well established and predictable” to “unknown and random”. A common technique utilized for reducing the voltage spikes is a Transient Voltage Surge Suppression/Surge Protection Device TVSS/SPD. A general guideline for suppressing high voltage transients utilizes a network or distributed transient voltage surge suppression configuration; one black box consisting of a mega TVSS/SPD does not suppress all types of high voltage transients for the entire electrical power system. The DC power supply is an ideal location to conduct this operation as part of a system for eliminating certain types of high voltage transients. Most utilization equipment already contain TVSS/SPD in the front end of their respective circuitry. Qualification requirements of aircraft AC and DC utilization equipment specified in MIL-HDBK-704 require five consecutive high voltage transients for each test condition (i.e. high voltage waveform) [7], [8]. The number and frequency of high voltage transients for actual aircraft operational conditions are generally unknown. For this reason, it is desirable to provide additional DC bus protection from high voltage transients in order to extend the life of utilization equipment resulting in a more reliable aircraft electronic system and reduced downtime along with operational costs of repair and maintenance.

Aircraft power system specifications indicate that high voltage transients range from 50 V to 80 V on the 28 VDC bus [4], [8]. These transients are caused by various events. Some transients are load-induced when a high current is changed or switched off. High voltage AC transients at the input of various power supplies are a common cause for high voltage DC transients; these AC transients are transmitted through the DC power supply to the 28 VDC bus as shown in Figure 7.

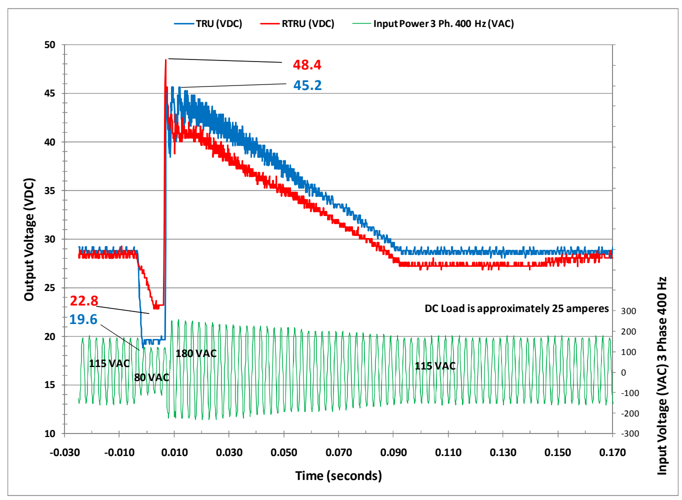

Figure 7: Output Voltage Response to Input Transient for TRU and a Regulated RTRU

Figure 7 shows the AC voltage change from 115 VAC to 80 VAC at time zero and then a rise to 180 VAC at 10 ms. The input AC voltage returns to 115 VAC at 100 ms. The example demonstrated here is created from the published power quality specification described as curve MM in MIL-HDBK-704-3 [7]. The output voltage response of a TRU caused by this low and high voltage AC transient falls to 19.6 VDC and rises to 45.2 VDC. The output voltage of a regulated RTRU also falls, but to a lesser extent at 22.8 VDC and rebounds slightly higher at 48.4 VDC for its maximum voltage condition.

The PCTRU contains a DC Bus Hold-up Device and Transient Voltage Surge Suppression/Surge Protection Device TVSS/SPD sufficient to source loads during low voltage transients and limit high voltage transients from being generated or transmitted through the power supply to the DC bus. This effect is shown in Figure 8 where the low voltage of the PCTRU is 26.8 VDC compared with 19.6 VDC and 22.8 VDC exhibited by the TRU and RTRU, respectively.

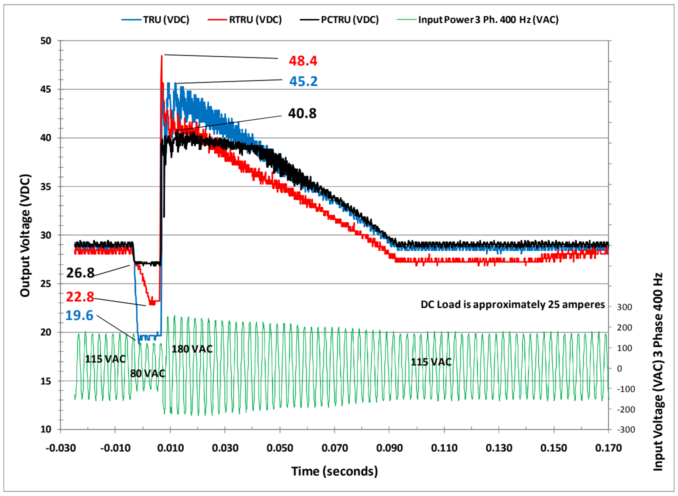

Figure 8: Output Voltage Response from a TRU, RTRU and PCTRU

The PCTRU suppresses the high voltage surge to 40.8 VDC compared with 45.2 VDC and 48.4 VDC exhibited by the TRU and RTRU, respectively. The design objective of the TVSS/SPD circuit in the PCTRU is to eliminate certain types of high voltage transients that normally range from 40-80 VDC and higher. Actual aircraft conditions have been measured that exceed 200 VAC resulting in DC voltage transients of 70-80 volts and are undesirable for DC utilization equipment. The PCTRU limits these high voltage transients of 70-80 volts to approximately 40 volts.

The effect of this is intended to increase the overall DC system reliability and reduce operational costs by reducing the high voltage transients subjected to DC utilization equipment and provide longer service life for electronic systems.

VOLTAGE MODULATION – Voltage modulation is the variation in amplitude of a voltage waveform with respect to time. Various AC to DC power converter topologies utilized in aerospace applications ranging from unregulated to regulated exhibit unique power quality characteristics when subjected to pulsed loads. Qualifying specifications require tests that subject these power supplies to static and shock loads, which do not simulate repetitive dynamic (i.e. pulsed) loads. Dynamic loads from various systems can operate in a pulsed loading condition and may present undesirable effects with respect to DC power quality on the aircraft DC bus. These loads can be pulsed on and off with a variable amplitude and frequency, which may cause DC power management systems to respond in various forms. Feedback controlled regulated power supplies exhibit classical voltage responses of overshoot and undershoot when subjected to repetitive dynamic loads. Output system inductance can also cause positive and negative voltage spikes when pulsed loads are present. The PCTRU contains a passive circuit that reduces these voltage modulations to a level that is considered insignificant due to their small amount of energy content. The military specification MIL-STD-704F discusses the requirements for an aircraft power system when dynamic loads are present. Effects of pulsed loads are described in MIL-STD-704F as, "…a potential cause of unacceptable voltage modulation. Hence large pulsed loads may require excess power source capacity or dedicated power sources to protect other aircraft equipment. The utilization equipment designer should strive to minimize the current modulation produced by pulsed loads." A possible rogue condition analogous to tsunamic waves may occur when one or more subsystems (i.e. DC loads) exist on a DC bus that exhibits pulsed loads. These subsystems perform normally when tested in the power system during individual operational conditions, but when working simultaneously may cause a surge of voltage modulation resulting in a range of faults while the underlying cause remains unknown.

Some examples of voltage modulation caused by pulsed loads from several power supply topologies are shown in Figures 9-12. These power supplies vary from low ripple to standard ripple and unregulated to regulated with the PCTRU shown in Figure 13. All of these power supplies are designed for 200 amperes continuous duty for aerospace applications. Load description: The static load is 50 amperes with a pulsed load of 150 amperes resulting in an average load of 125 amperes.

Figure 9 is the output response of a standard ripple voltage traditional TRU with 1.8 $V_{pk\text{-}pk}$. It exhibits high voltage swings from 35.8 VDC to 20.2 VDC when subjected to these pulsed loads.

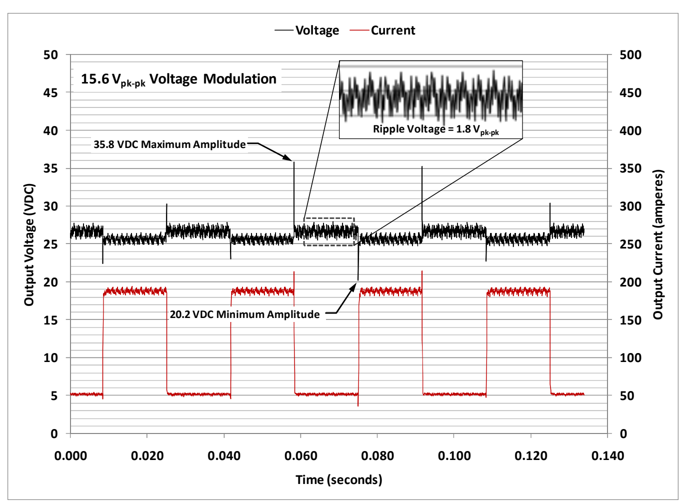

Figure 9: Output Response of a Standard Ripple Voltage Traditional TRU

Figure 10 is the output response of a low ripple voltage traditional TRU with 0.4 V_{pk-pk}. It exhibits high voltage swings from 41.3 VDC to 16.7 VDC when subjected to these pulsed loads. These voltage swings are caused by the output inductance of the circuit.

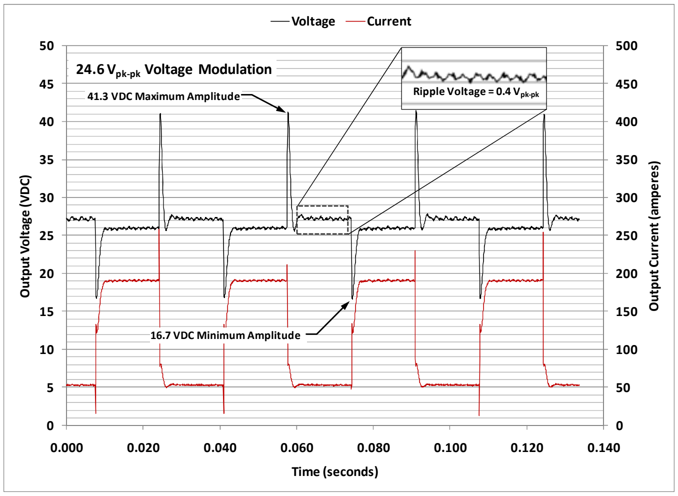

Figure 10: Output Response of Low Ripple Voltage Traditional TRU with High Positive and Negative Voltage Spikes

Figure 11 is the output response of a standard ripple voltage RTRU at 1.1 V_{pk-pk}. It exhibits the typical overshoot up to 30.1 VDC with an undershoot of 25.9 VDC.

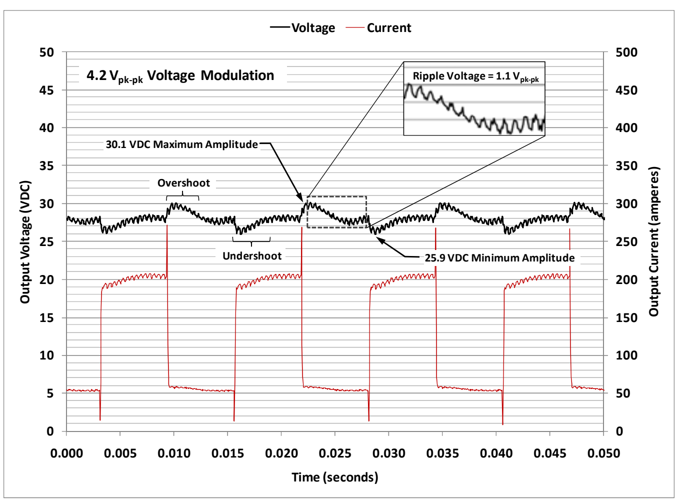

Figure 11: Output Response of a Regulated RTRU Exhibiting 4.2 V_{pk-pk} Modulation

Figure 12 is the output response of a moderately low ripple voltage RTRU at 0.7 V_{pk-pk}. It exhibits the typical overshoot up to 30.9 VDC with an undershoot of 25.4 VDC.

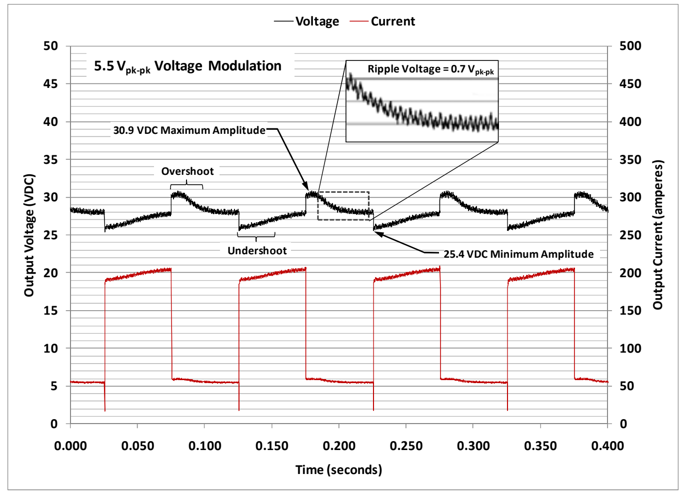

Figure 12: Output Response of a Regulated RTRU Exhibiting 5.5 V_{pk-pk} Modulation

Figure 13 is the output response of the PCTRU with a ripple voltage of 0.3 V_{pk-pk}. The PCTRU exhibits an 85 percent improvement with the maximum and minimum voltage in this pulsed load condition of 29.9 VDC and 26.0 VDC, respectively. The PCTRU exhibits the lowest ripple voltage and least amount of voltage modulation when subjected to this type of pulsed loading condition.

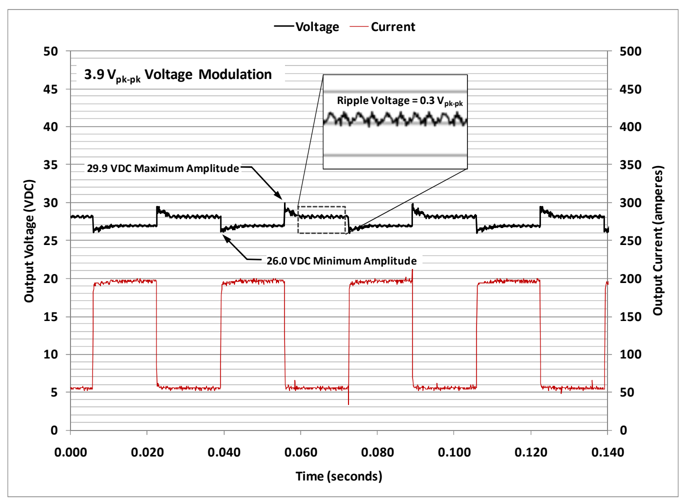

Figure 13: Output Response of a PCTRU Exhibiting 3.9 V_{pk-pk} Modulation

These characteristics of voltage modulation are intended to raise awareness of the potential effects of pulsed loads for the aircraft DC power system. The results of these evaluations give data to support aircraft electrical power system design activities for current and future applications involving advanced electronic aircraft.

CONCLUSION

The additional capabilities of the PCTRU provide performance advantages while achieving the objective of preserving reliability for aerospace applications. These power quality characteristics are superior to existing power supplies and exceed industry specifications with respect to DC voltage stability. The characteristic of voltage regulation is improved by approximately 50 percent. Ripple voltage is attenuated by 90-95 percent at approximately 0.20 $V_{pk\text{-}pk}$ with respect to traditional TRU designs. Power interruptions, both "blackouts" and "brownouts", are eliminated for normal and abnormal conditions. Overvoltage conditions (i.e. high voltage transients) are suppressed at the DC output of the power supply to approximately 40 VDC in order to increase the life of semiconductor devices in advanced electronic utilization equipment. Voltage modulation caused by dynamic or pulsed loads is improved by 85 percent. The overall reliability of the PCTRU is not significantly affected by these additional features since they function in parallel and work independently of the main power path of the basic TRU topology. The PCTRU provides a practical solution for stabilizing the aircraft DC bus for advanced electronic systems utilizing digital and COTS subsystems.

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