

Standardized Electrical Power Quality Analysis in Accordance with MIL-STD-704

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ABSTRACT

MIL-STD-704 defines power quality in terms of transient, steady-state, and frequency-domain metrics that are applicable throughout a military aircraft electric power system. Maintaining power quality in more electric aircraft power systems has become more challenging in recent years due to the increase in load dynamics and power levels in addition to stricter requirements of power system characteristics during a variety of operating conditions. Further, power quality is often difficult to assess directly during experiments and aircraft operation or during data post-processing for the integrated electric power system (including sources, distribution, and loads). While MIL-STD-704 provides guidelines for compliance testing of electric load equipment, it does not provide any instruction on how to assess the power quality of power sources or the integrated power system itself, except the fact that power quality must be satisfied throughout all considered operating conditions. Thus, the standard leaves much room for interpretation while significantly different results can be obtained by adjusting the framework parameters of the power quality analysis. This paper addresses power quality analysis and its ramifications during post-processing of simulation, experiment, and prototype aircraft data. It provides methods to evaluate transient, steady-state, and frequency metrics defined in MIL-STD-704 in addition to several data visualization techniques, in particular for the distortion spectrum analysis. Further, appropriate data acquisition rates for the analysis of the individual metrics are addressed. The discussion culminates in several recommendations for the analysis of transient and

frequency-domain specifications in terms of framework parameters and methods. These recommendations, in one form or the other, are an attempt to amend MIL-STD-704 and further standardize power quality analysis. Finally, a Matlab toolbox is introduced that allows the automated power quality analysis of experimental or simulation data based on the techniques discussed in this paper.

INTRODUCTION

With the continued advance in more-electric aircraft (MEA) systems, challenges arise in the design of the electric ac and dc power system (EPS) components in terms of delivering necessary peak and average power to the appropriate loads while maintaining voltage and current waveforms that satisfy specifications presumed by these components. Future MEA systems will have to deal with increased capability demands from electromechanical flight and engine actuation, high-power radar, electrically-driven power and thermal management systems, directed-energy weapons, etc. In order to meet this demand, alternative and improved EPS architectures are considered that include additional power sources (low-spool generator, batteries, electrical accumulator units) and distribution and filtering technologies (solid-state power controller and advanced capacitor technologies). One of the challenges in the design, analysis, and evaluation of existing and new EPS architectures is determining if the power quality characteristics set forth in standards such as MIL-STD-704 [1] are satisfied. (Note that MIL-STD-704 refers to Revision F of said standard, but the context of this paper can be applied to any previous revisions or related specifications without much difficulty.)

MIL-STD-704 defines the power quality of ac and dc aircraft EPS in terms of steady-state, transient, and frequency spectrum characteristics. The definitions incorporate various measures such as average, root-mean-square (RMS), distortion, etc., for a given voltage signal. Experimental test conditions and procedures for the various type of electrical aircraft power are outlined in supplemental documents [2]. They provide instructions for a complete MIL-STD-704 compliance test of aircraft utilization equipment. However, similar instructions for testing of power generation/source equipment and the whole integrated aircraft EPS itself have not been standardized and are assumed to be specified individually for each aircraft. The attempt to create such standardized test instructions is questionable since both generator and aircraft EPS behavior depend strongly on the loads and are difficult to characterize with individual component tests. Further, it does not remove the challenge of analyzing power quality during actual aircraft operation, which is the most important time that power quality must be satisfied. Thus, while MIL-STD-704 leaves room for various interpretations of power quality compliance testing in an actual aircraft EPS, the focus should be on standardization of appropriate techniques that are valid for the analysis of components and integrated EPS operation. This paper attempts to provide such standardized techniques and recommendations as described below.

In recent MEA programs, the demand for more power and better power quality resulted in the installation of integrated vehicle system and subsystem ground test capabilities at both the airframer and government facilities. The possibility of analyzing and optimizing subsystem integration, especially at the EPS level, results in generation of a significant amount of test data that must be analyzed for power quality compliance. Thus, it is necessary to provide a uniform approach to the power quality analysis within an MEA platform that will provide compliance statements that can be relied on by all involved parties, be it the customer, system integrator, or subsystem component supplier. Because the methods discussed in [2] are not applicable to integrated aircraft EPS or power generation/source equipment, power quality is often analyzed ad hoc during equipment integration or aircraft prototype testing. In such circumstances, measurement equipment such as spectrum and distortion analyzers are not available and relevant data must be acquired and post-processed in separate steps. While many of the definitions in MIL-STD-704 can be applied to direct measurements as well as post-processed data, the need for data acquisition and software post-processing introduces additional framework parameters that can significantly influence the results of compliance checks. Thus, the standard leaves much room for interpretation in terms of best practices on how to analyze power quality. For example, minimum data acquisition rates and signal filtering specifications for the individual power quality requirements are not defined. In another example, when analyzing the distortion frequency spectrum of a

voltage signal, the frequency spectrum of the signal is commonly calculated across timeframes (windows) of a certain length. The choice of the window length, which is not defined in MIL-STD-704, significantly influences the distortion spectrum results. Generally, a uniform approach for power quality analysis within an aircraft EPS has not been established to date, and different results and evaluations can be obtained by adjusting the framework parameters of the power quality analysis.

This paper investigates power quality analysis in the sense of MIL-STD-704 applied to integrated EPS of MEA. Primarily, the focus is on 270 V dc power systems, but the provided discussion should generally be extendable to ac and low-voltage dc power systems. First, a summary of relevant MIL-STD-704 specifications and definitions is provided, including formal algorithms and associated parameters to analyze the specifications in a post-processing fashion. Then, the transient specifications are more closely investigated and appropriate procedures and techniques are discussed that allow the analysis of transient phenomena. Next, several frequency-domain techniques and their limitations are discussed that allow the analysis of the voltage distortion spectrum and compare them to the limits defined in MIL-STD-704. The utilized methods range from Fourier Transforms (FT) to Short-Time Fourier Transforms (STFT) and wavelet analysis. For the analysis of both the transient and frequency-domain specifications, recommendations are then given about proper procedures and parameters settings as potential amendments to MIL-STD-704. Finally, to facilitate post-processing data analysis with many of the methods discussed in this paper, the Power Quality Analysis Toolbox (PQATool) available for Matlab is introduced.

RELEVANT SUMMARY OF MIL-STD-704

This section summarizes the MIL-STD-704 definitions and requirements utilized in this paper for the analysis of 270 V dc power quality. While the scope of MIL-STD-704 primarily targets electric power quality at the input terminals of electric utilization equipment, the standard does require that the aircraft EPS characteristics comply with the standards' specified limits throughout all operating conditions. This naturally includes the operation of a completely integrated aircraft EPS consisting of power sources, distribution network, protection and control devices, and loads. However, MIL-STD-704 does not cover induced voltage spikes and electromagnetic interference (EMI, covered in MIL-STD-461 [3]).

DEFINITIONS

Operating conditions

MIL-STD-704 defines six distinct aircraft EPS operating conditions and the expected behavior within and during transfers between these operating conditions. *Normal operation* occurs in the absence of any fault, malfunction, engine start, or Auxiliary Power Unit (APU) battery start. *Abnormal operation* occurs during a malfunction or failure within the EPS and during removal thereof. *Electric starting operation* is a special case of normal operation with extended voltage limits that occurs during propulsion engine electric start or APU battery electric start. *Emergency operation* occurs following the loss of the main power source where the EPS is powered by a limited electric power source. *Power failure* defines the operation of equipment during short-term and long-term loss of power. Finally, *transfer operation* occurs when the EPS transfers between power sources. In such events, the *transfer operation characteristics* of voltage and frequency shall vary between zero and normal operating limits for no longer than 50 ms (to accommodate for opening and closing of transfer contactors). After completion of a transfer, a normal transient event may occur.

Transients

Transients are defined as any change in value (of voltage, current, power, etc.) due to events in the EPS. This includes normal and abnormal disturbances or momentary power interruptions. *Lesser transients* are transients that do not exceed the steady-state limits. *Normal transients* exceed steady-state limits but stay within the specified normal transient limits. *Abnormal transients* are transients that are a result of an abnormal disturbance, exceed the normal limits, and eventually return to steady state. Finally, *steady state* describes the condition where EPS characteristics stay within the normal operating limits, including lesser transients, throughout an arbitrarily long period of time.

Metrics

Several metrics are defined in MIL-STD-704 without providing actual formulas for their calculation. For transparency, formulas describing the relevant metric are presented here. *Steady-state dc voltage*, V_{dc} , is defined as the time average of the *instantaneous voltage* $v(t)$ over a window starting at T_1 , ending at T_2 , and not exceeding 1 s in length:

$$V_{dc} = \frac{1}{(T_2 - T_1)} \int_{T_1}^{T_2} v(t) dt . \quad (1)$$

Voltage ripple, v_r , is the variation about the steady-state dc voltage during steady-state operation

$$v_r(t) = v(t) - V_{dc} . \quad (2)$$

MIL-STD-704 defines the *ripple amplitude* as the maximum absolute value of the voltage ripple in steady state. This definition is not associated with a timeframe, i.e. it is not defined across which time window this definition is supposed to be applied. The most convenient and logical selection is to choose the same window as for the calculation of V_{dc} . However, using this definition removes a significant amount of information, as it provides only one value describing the voltage behavior across the selected window. This severely limits its usability, especially if the applied loads results in significant voltage transients. Thus, throughout this paper, *peak ripple*, v_p , defined as the absolute value of v_r at each point in time, is utilized

$$v_p(t) = |v_r(t)| = |v(t) - V_{dc}| . \quad (3)$$

This metric allows ripple to be analyzed for a given signal and removes the ambiguity of determining a maximum ripple voltage across a given timeframe. It allows an engineer to identify the regularity of the ripple amplitude and spot sporadic peak values that would not be possible with the given definition of the ripple amplitude.

Distortion V_d in an ac system is the RMS value of the waveform exclusive the RMS voltage of the fundamental frequency $V_{ac(1)}$

$$V_{d,ac} = \sqrt{\frac{1}{(T_2 - T_1)} \int_{T_1}^{T_2} v(t)^2 dt - V_{ac(1)}^2} . \quad (4)$$

In a dc system, Eq. (4) must be slightly adjusted to remove the dc component from the distorted signal

$$V_{d,dc} = \sqrt{\frac{1}{(T_2 - T_1)} \int_{T_1}^{T_2} (v(t) - V_{dc})^2 dt} . \quad (5)$$

In MIL-STD-704, the distortion is determined in dB in comparison to 1 V_{RMS} as

$$V_{d,dB} = 20 \log_{10}(V_d) . \quad (6)$$

The *distortion factor* d_f is the ratio of the distortion to the fundamental RMS value in an ac system or the ratio of the distortion to the steady-state dc voltage in a dc system

$$d_{f,ac} = \frac{V_{d,ac}}{V_{ac(1)}}, \quad d_{f,dc} = \frac{V_{d,dc}}{V_{dc}}. \quad (7)$$

Finally, the *distortion spectrum* provides a quantification of the distortion in frequency domain. It can be calculated using the Fast Fourier Transform (FFT) and/or the Discrete Fourier Transform (DFT).

Note that the actual implementation of Eqs. (1),(2),(3),(4),(5),(6),(7) used in this paper is based on a sliding window technique similar to that shown in Figure 1, where a window of length $\Delta T = T_2 - T_1$ is slid across the time-axis at fixed time steps. The continuous evaluation of V_{dc} and d_f across the whole window length for each time step creates a data point at the center of each window location. Interpolating between these data points creates the continuous waveforms for V_{dc} and d_f (also referred to as moving average and distortion, respectively).

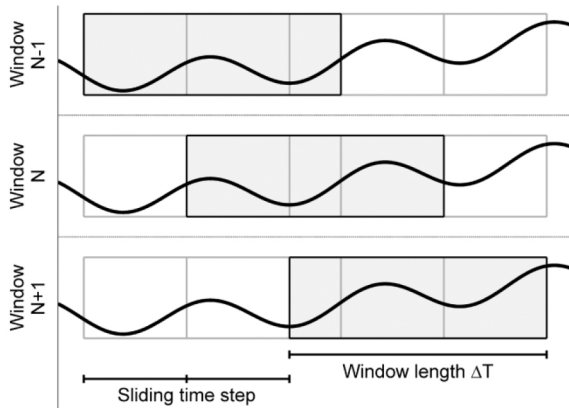


Figure 1. Sliding window technique used for average, distortion factor, and distortion spectrum evaluation.

270 V DC POWER QUALITY REQUIREMENTS

The power quality requirements for the 270 V dc EPS are limited to the definition of normal and abnormal operation. Requirements during emergency operation are the same as the requirements for normal operation. Other operating condition requirements must be defined individually for each aircraft. During normal operation, the steady-state voltage limits are 250 V at the lower end and 280 V at the upper end, which are also the limits defined for lesser transients. The limits on the distribution factor and peak ripple are 0.015 and 6.0 V,

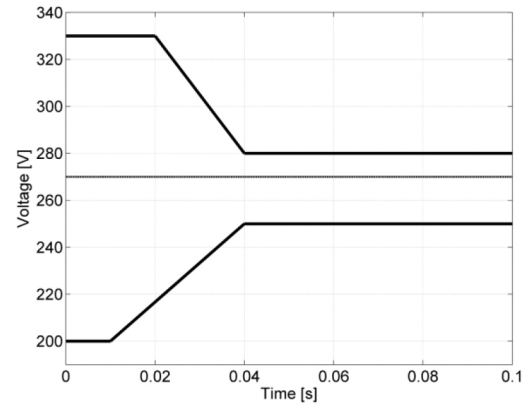


Figure 2. Normal voltage transient envelopes for 270 V dc EPS.

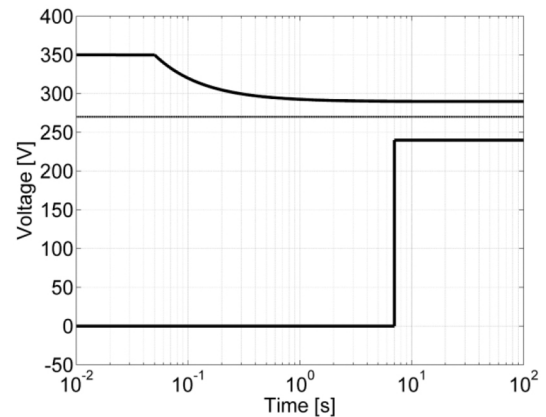


Figure 3. Abnormal voltage transient limits for 270 V dc EPS.

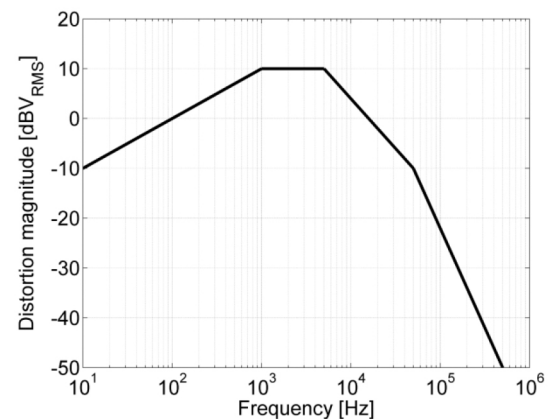


Figure 4. Maximum distortion spectrum for 270 V dc EPS, measured in dB from 1 V_{RMS}.

respectively. The voltage transient envelopes during normal operation (normal transients) are shown in Figure 2. Based on this chart, any kind of transient disturbance during normal operating conditions must vanish to within steady-state limits