Design for Reliability Techniques — Worst Case Circuit Stress Analysis

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Abstract

This paper discusses using Worst Case Circuit Stress Analysis (WCCSA) as a technique for ensuring the reliability of electronic circuits under most operating conditions by accounting for component variability. Both the initial variability and the effects of component aging are considered, as are conditions external to the circuit. This Design for Reliability analysis provides the development team with insight to product robustness, enabling early detection and minimizing the risk of problems in the end user applications.

Introduction

During the early development of Advanced Energy (AE) products, it is critical for engineers to quantify the design margins of all electronic circuits. The most revealing method is a Worst Case Circuit Stress Analysis (WCCSA), which determines the stress levels on each component when variable parameters are at values that maximize stress on the component being analysed [1, 2]. The variable parameters to be considered include the initial and aging tolerances on components in addition to parameters external to the circuit, such as supply voltages and currents, operating frequencies, and local ambient temperatures. When each of these variable parameters are at

Table of Contents

their maximum values for stressing the component being analysed, the resulting stresses can be quantified and compared to manufacturer ratings, AE derating guidelines, and cross-industry best practices. The end goal is to ensure component, subsystem, and product robustness across the entire operating space [3-5].

It is important to note that, despite the confusing industry standard nomenclature, there is not a single “worst case” for the product or even an individual component. The WCCSA is comprised of many discrete combinations of conditions under which components are at their most stressful operating parameters. As an example, a resistor can have voltage and power stress, the latter of which is correlated to current and temperature. Under two different field usage scenarios, the same resistor may experience high voltage stress, power stress, or both. Therefore, a WCCSA must encompass all of these “worst cases.” This example applies to all electronic parts in the circuit being analysed.

Process for Analysis

A general process flow for conducting a WCCSA is illustrated in Figure 1. At the outset, engineers work to understand the range of field applications in which the product and constituent circuits are installed. At AE, lessons learned from prior products are incorporated into the analysis as appropriate. Various numerical methods are used in conjunction with circuit simulation tools to develop a comparison between the performance specifications and modelled behavior. If modifications are necessary, a regression analysis is undertaken. The circuit is implemented when there is adequate design margin.

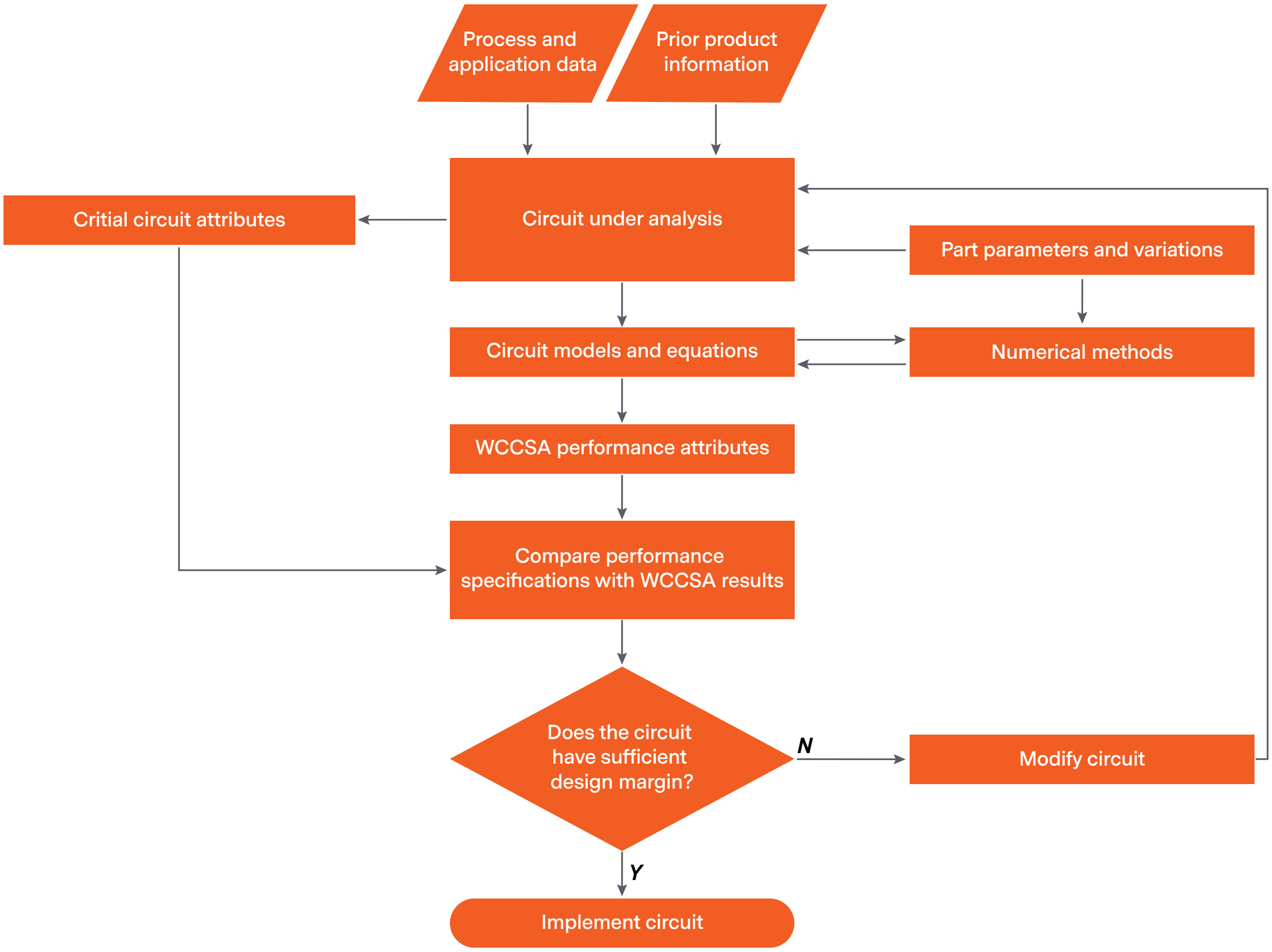

Figure 1 – Worst Case Circuit Stress Analysis process flow, adapted from [2, 3].

The results of this analysis and any associated circuit modifications are an important element in the initial development process. As with other Design for Reliability techniques at AE, the analysis is iterative and updated, as our technical teams continually refine their understanding of customer usage.

Methods

Conducting a WCCSA is clearly a nontrivial exercise, so standardized methods must be used to provide consistent results between AE engineering groups, contain the scope, and expedite the process. Key elements of the techniques are presented in this section.

Component variation

All electronic components have variability. The most familiar types are the datasheet tolerances, such as the ±5% rating on the resistance of a resistor. Tolerance data is readily available and is routinely incorporated into designs. Other sources of variation include the effects of component aging. A widely-used example is the progressive decrease in capacitance and increase of equivalent series resistance (ESR) of aluminium electrolytic capacitors. The magnitude and change per unit time of these key parameter shifts depend on the capacitor design type, manufacturing controls, and specific application [6-8]. A basic equivalent circuit for an electrolytic capacitor is shown in Figure 2. While only the capacitance is desired, there are parasitic elements present in all physically realizable components.

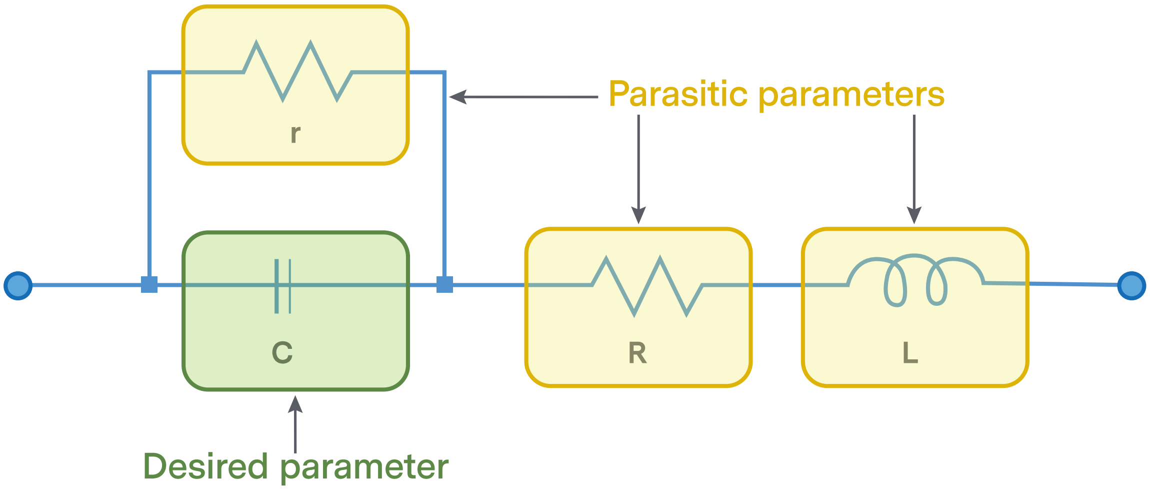

Figure 2 – Equivalent circuit of an electrolytic capacitor.

Table 1 — Parameters relevant to WCCSA of an electrolytic capacitor.

Parameter	Description	Variability	
		Initial tolerance	Change due to aging
C	Capacitance	Moderate	Moderate
r	Equivalent parallel resistance of anode oxide film	Low	Low
R	Equivalent series resistance	Moderate	Low
L	Equivalent series inductance	Low	None

Numerical methods

Considering the large amount of analysis to be done for a typical WCCSA, engineers are always looking for ways to simplify the technique without sacrificing the quality of the result. Carefully choosing the types of numerical methods used can expedite the analysis. One such technique is to analyze steady state parameters by inspection for parts that have a small range of stresses regardless of the product application, such as those in low power dissipation, low voltage subsystems. Customized spreadsheets are common and are utilized at AE as appropriate. An example of WCCSA by inspection is illustrated in Table 2. The datasheet parameters for a 3 kΩ resistor are noted and derating according to AE guidelines is calculated. The use case in the specific circuit is the next input. The outcomes show adequate margin above the manufacturer specifications and AE derating guidelines, even at the most stressful condition this resistor is exposed to.

Table 2 — Example of steady state analysis by inspection.

Part Specifications						Part derating	
Part Description	V_{MAX} [V]	P_{MAX} [W]	Resistance Tolerance [%]	T_{MAX} [°C]	Thermal Transfer [°C/W]	V_{MAX} [V]	P_{MAX} [W]
SMD resistor; 3.01 kΩ; 1/10 W; 0603	75	0.1	1.0%	70	124	52.5	0.06

Usage of the part in the specific application						Outcomes of WCCSA by inspection		
$V_{NOMINAL}$ [V]	$V_{WORST\ CASE}$ [V]	$P_{NOMINAL}$ [W]	$P_{WORST\ CASE}$ [W]	Ambient Temp of Component [°C]	Temp, worst case calculated [°C]	Voltage Margin [%]	Power Margin [%]	Thermal Margin over derating [°C]
15.0	17.7	0.0257	0.0290	50	53.6	33.7%	48.3%	16.4

When the inspection technique is not suitable, more complex methods are undertaken [9-13]. The most common are shown in Table 3.

Table 3 – Numerical methods for analysis, adapted from [1].

Analysis Method	Advantages	Disadvantages
Monte Carlo	▪ Most realistic estimate ▪ Outputs include a probabilistic description of circuit behaviour	▪ Advanced EDA tools or skils required ▪ Requires knowledge of the probability density function for part parameters
Extreme Value	▪ Easily attainable through simple analysis ▪ Statisical inputs not required	▪ Outputs can be overly pessimistic ▪ Can drive unnecessary overdesign
Root Sum Squared	▪ Statistical inputs not required	▪ Requires knowledge of standard deviation for part parameters ▪ Assumes Gaussian distribution of parameters ▪ Not well integrated into most EDA tools

Monte Carlo analysis provides the most realistic estimate of the range of stresses, including a probability density function of the possible outcomes for a given set of inputs. This is particularly useful if it is known that some parameters have non-Gaussian distributions. Figure 4 uses AE volume production data to show this type of variability. This data is comprised of approximately 10,000 samples of an off-the-shelf purchased part with a datasheet critical parameter minimum of 90 and a maximum of 120. Note that while all parts meet this specification, there is a distinct bimodal distribution due to supplier production shifts. AE engineers use this type of data as an input to other tools and statistically quantify any risks to robust design margin [14-16].

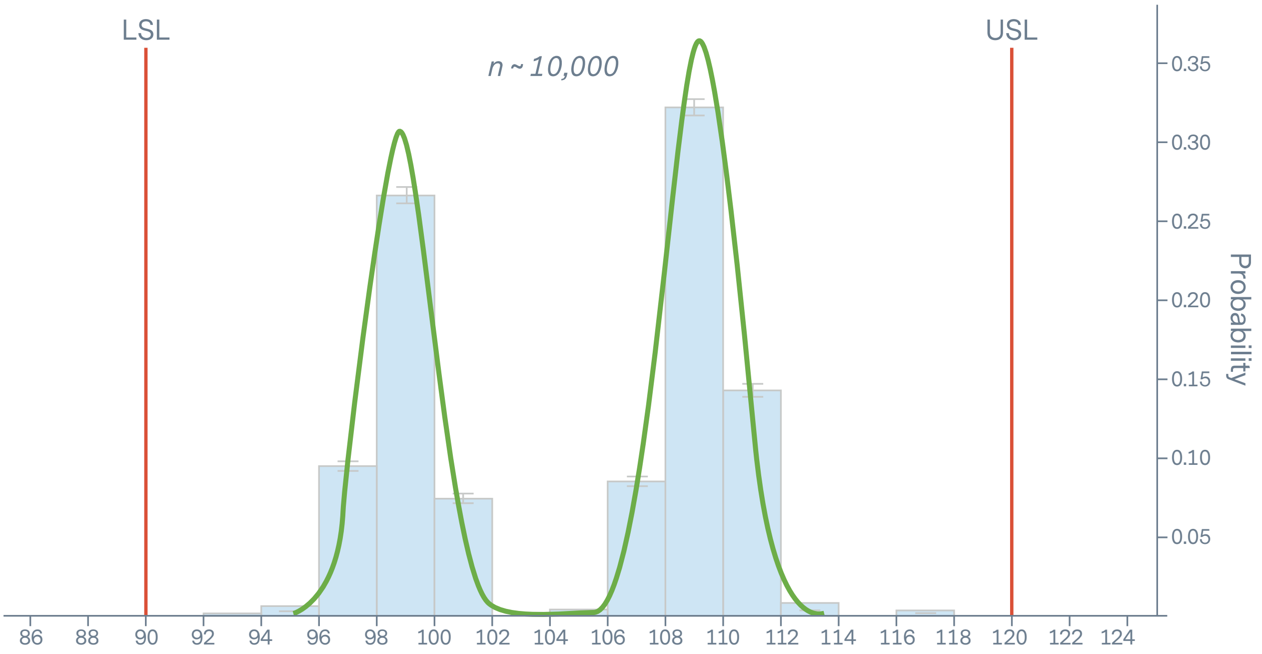

Figure 4 – Bimodal distribution of a critical parameter.

Extreme Value analysis has the benefit of being straightforward to implement, as the worst-case values are used for all calculations, but the associated probabilities are not known. The Root Sum Squared method has drawbacks which limit practical use in most cases.

Circuit simulation

The three numerical methods described require software tools for analysis. Engineers at AE regularly combine circuit simulation, numerical computing, and statistical analysis tools for WCCSA.

Both initial tolerance and aging variability can be shown in a simple example. Figure 5 shows a 200 run simulation of pulsed current through a new electrolytic capacitor, as may be seen in an AE product. Standard datasheet tolerances for capacitance and ESR were used. Note that the distribution in both the time and magnitude domains is due to initial tolerances. The peak current varies from approximately 37 A to 48 A. Referring to Figure 6, published values for degradation in these key parameters has been incorporated into the model. The peak current has been reduced to the range of 25 A to 32 A, approximately 50% from the new part. Whether this still meets the circuit application needs is case dependent, but this example is indicative of a result that warrants further attention from the engineering group.

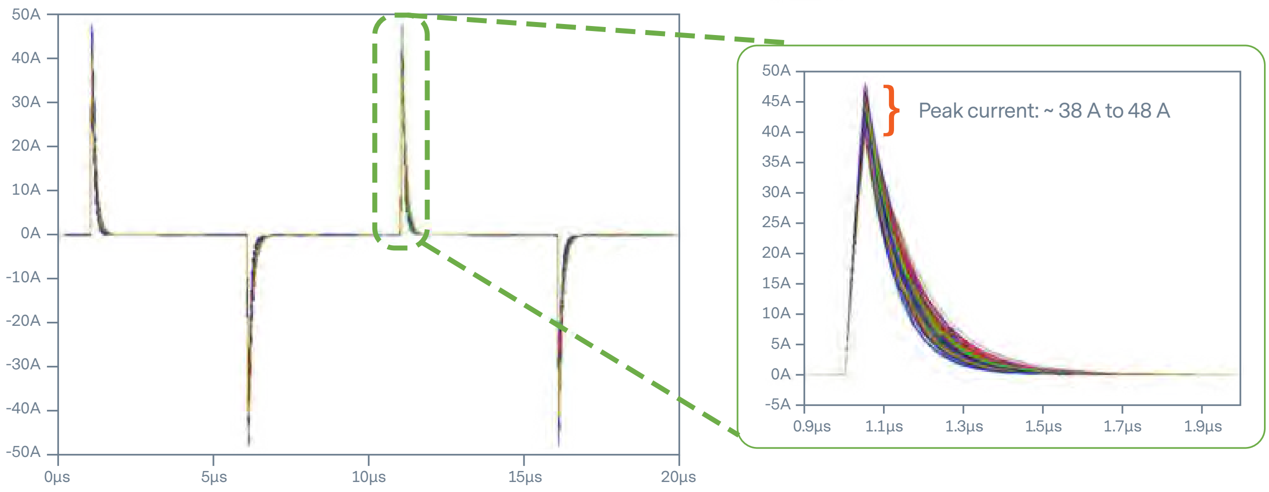

Figure 5 – Simulation of current through a new electrolytic capacitor.

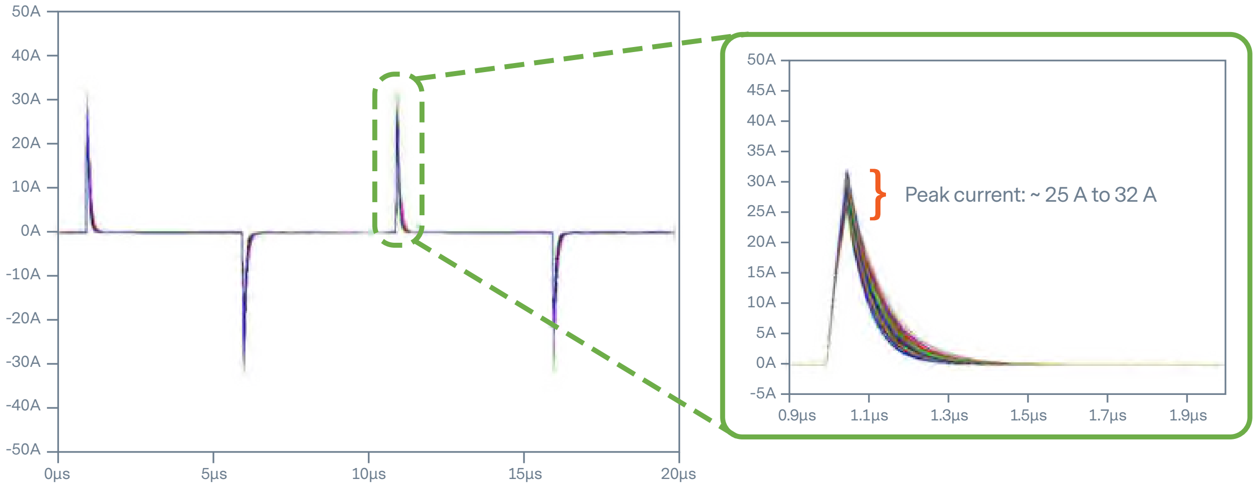

Figure 6 – Simulation of current through an aged electrolytic capacitor.

Dynamic and Transient Considerations

Additionally, when considering worst case conditions, dynamic and transient stresses resulting from actual field use conditions must be incorporated. Examples of transient condition stresses that affect AE products include plasma ignition, start-up inrush current, AC mains disturbances, and abrupt changes to process gas flow rates. Figure 7 shows the hypothetical effect of a load transient on an open loop 13.56 MHz RF power delivery system. Parts rated for 500 WVDC would have adequate design margin for a 1 kW output, as the potential would be a maximum of 315 V. However, plasmas for semiconductor processes are often unstable. As the lower portion of Figure 7 demonstrates, a momentary change in the plasma impedance can cause the voltage at the output of the generator to exceed 550 V. The previously considered 500 WVDC parts would not have sufficient design margin in this case and would require uprating to ensure high reliability.

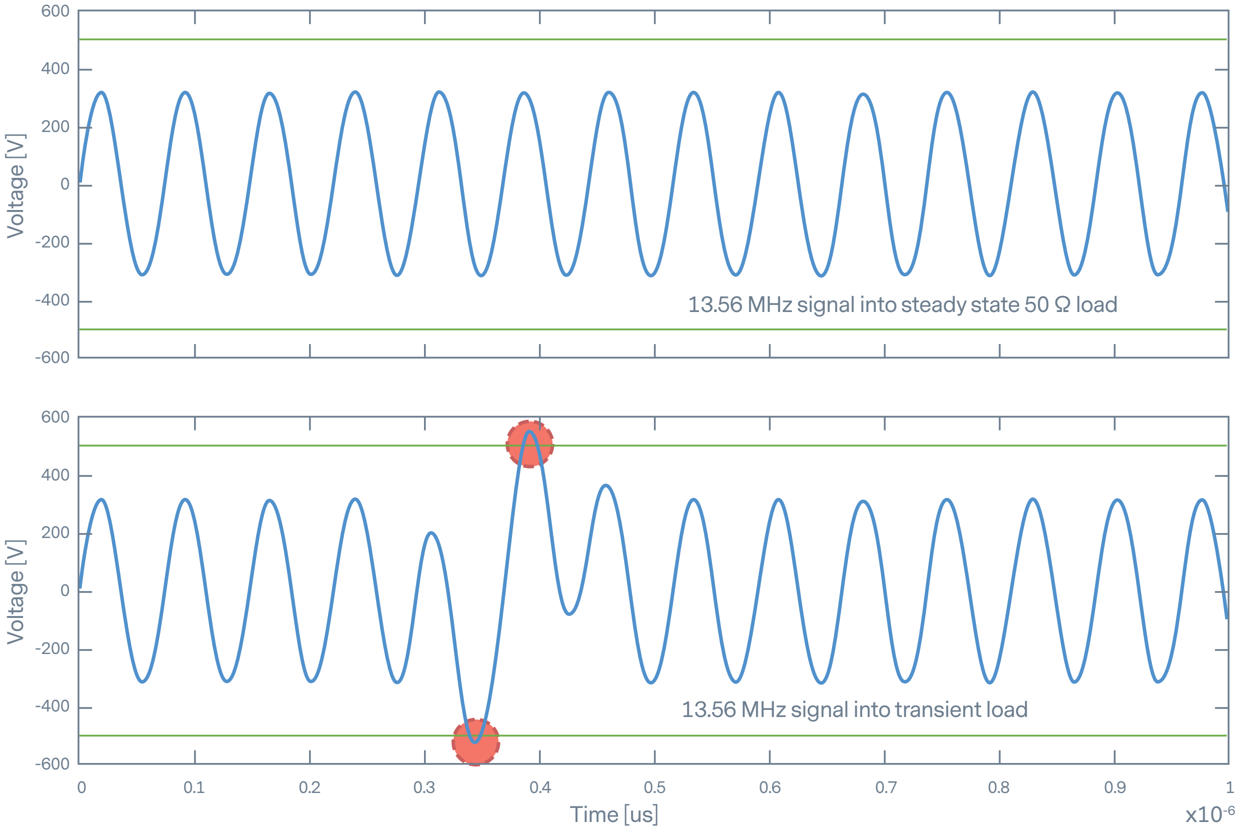

Figure 7 – Example of transient WCCSA conditions.

Summary

A methodical and rigorous Worst Case Circuit Stress Analysis is a crucial early Design for Reliability technique that helps technical experts quantify the stresses on electrical parts over the entire product operating space. Initial and aging variability must be considered, and multiple numerical methods are used to accelerate development. Because Advanced Energy products are used in a broad array of mission critical applications, special consideration is given to ensure product robustness under many transient conditions.

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