

Impact of Transient Operating Conditions on Electrical Power System and Component Reliability

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ABSTRACT

Transient operating conditions in electrical systems not only have significant impact on the operating behavior of individual components but indirectly affect system and component reliability and life. Specifically, transient loads can cause additional loss in the electrical conduction path consisting of windings, power electronic devices, distribution wires, etc., particularly when loads introduce high peak vs. average power ratios. The additional loss increases the operating temperatures and thermal cycling in the components, which is known to reduce their life and reliability. Further, mechanical stress caused by dynamic loading, which includes load torque cycling and high peak torque loading, increases material fatigue and thus reduces expected service life, particularly on rotating components (shaft, bearings). This article investigates the aforementioned stress mechanisms and provides analysis techniques and metrics to quantify the impact of transient operating conditions onto system and component reliability and life. It is shown that reducing transient loading in an electrical power generation system of a more-electric aircraft, for example through the inclusion of an appropriately controlled energy storage device, can have a significant impact on reliability and life of the power generating system and its components. Specifically, winding insulation, power electronic devices, rotating shaft structures, and bearings benefit from the reduced exposure to transient loading.

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INTRODUCTION

Electrical power system (EPS) components, such as electrical machines and power electronic converters, face many conditions that can have a detrimental impact on life and reliability [1] and are of a mechanical, electrical, and thermal nature. One specific aspect not discussed in detail in the literature concerning the reliability of such systems is the impact of changing electrical operating conditions (i.e., transient loading) on component life. Besides well-known power quality challenges, dynamic or transient loading in EPS can impact individual components connected to the EPS because of secondary effects associated with such transients [2]. Specifically, transient loads can cause additional loss in the electrical conduction path consisting of windings, power electronic devices, distribution wires, etc., particularly when loads introduce high peak vs. average power ratios. Additional loss contributes to heating of components and devices, which in turn decreases the life expectancy of power electronic devices, passive filtering components (capacitors and inductors), and wire and winding insulation systems. Further, the introduction of large dynamics can cause significant bus voltage ripple, which increases electrical stress on the

dielectric strength of insulation materials as well as on power electronic and passive components. Mechanical stress caused by dynamic loading, which includes load torque cycling and high peak torque loading, increases material fatigue and thus reduces expected service life, particularly on rotating components within the generator (rotor shaft, bearings) and upstream mechanical systems such as the gear box. Finally, high-frequency vibration in the kilohertz range, caused by current ripple introduced by switching power converters that translate into torque ripple on a generator's stator and rotor, further increases material and bearing fatigue and can significantly reduce reliability in generators, particularly if winding components on either stator or rotor are loose.

This article investigates the individual stress mechanisms and discusses their relation to specific failures and hence expected reliability and life. Specifically, it is shown that transient stress has a significant impact on life expectancy of winding insulation, bearings, rotating components, and power electronic devices. Further, technology and architectural changes to the electrical system are demonstrated to minimize electrical stress in individual components, thereby extending reliability and life.

The investigation uses transient simulation results from electrical generation systems (machine and power electronic inverter) as examples, for which relevant reliability results will be generated. Specifically, it is shown that the addition of a hybrid energy storage module (HESM) into the EPS significantly decreases the individual stresses and improves expected reliability and life in the generator mechanical system (including bearings and the gear box) as well as the electrical components (generator windings and power electronic switches). A HESM is essentially an optimized combination of energy storage devices such as batteries, capacitors, etc., that, in one possible arrangement, are coupled to an EPS through power electronic converters and intelligent controls similar to what has been introduced in [3]. The presented analysis approach and results are useful for component and architectural power system design for future equipment as well as addressing component and architectural design changes in legacy applications.

TRANSIENT STRESS MECHANISMS

Winding Insulation

It has been shown that maintenance related to stator winding insulation failure causes up to 50% of the downtime for a given electrical machine [1]. It is thus no surprise that the aging phenomenon of wire and winding insulation material has been studied for decades, and a variety of explanations and modeling approaches have been discussed. Commonly, the causes of insulation aging and failure (breakdown) have been shown to include electrical stress, thermal stress, mechanical stress, and environmental stress [4]. Naturally, the effects of electrical stress have been studied in the most detail, and several effects that contribute to the breakdown of insulation have been identified [4], including localized partial discharge, insulation surface erosion due to air/gas to insulation interfaces, electrolysis due to moisture, and molecular defects in the insulation polymers. These effects tend to be enhanced at higher temperatures, as insulation materials degrade to oxidation and hydrolysis. Mechanical stress is usually introduced by motion due to vibration and thermal expansion, and by bending of wires and cables which puts strain on certain parts of the insulation. Finally, environmental stresses are difficult to characterize and are application dependent, but can include radiation, humidity, and pressure.

While environmental and mechanical stresses are application dependent and very difficult to anticipate in generic reliability and life modeling of insulation materials, the effects of electrical and thermal stress have been studied and modeled in detail. Specific attention has been paid to the creation of multi-stress life models that consider both the electrical peak voltage and the temperature [5]. The most common life model combines experimentally-validated equations for electrical stress (exponential or inverse-power equations) and the Arrhenius (exponential) equation for thermal effects. These models have

shown to provide good agreement with experimental data for a variety of insulation materials, including polyimide insulation, which is commonly used in higher-temperature environments [6].

However, one caveat regarding these models that has been discovered in recent years is that they do not accurately predict insulation life in electrical machines driven by pulse-width modulated (PWM) power electronic converters [7,8]. Square-wave voltage waveforms with fast rise-times and high repetition rates (switching frequency) cause additional stress on the insulation that can significantly accelerate the insulation aging. There are a cascade of effects that are responsible for this phenomenon [9]. First, the fast rise-time of the voltage during turn-on (and turn-off) cause a traveling wave (transmission-line effect) in the machine's cables and its winding, which essentially amounts to wave reflections that can cause voltage magnitudes of up to two times the converter's dc voltage for short connection cables and up to three times the dc voltage for very long cables [9]. Further, due to the travelling effect of this pulse wave, up to 90% of the peak pulse voltage can drop across the first turn within the machine's winding, causing significant electrical stress on the turn-to-turn insulation in machines that have multiple turns per slot. The high repetition rate of these pulses significantly accelerates the aging process compared to line-operated motors. Hence, many of the developed insulation specifications utilized for electrical machines have been updated to include recommendations for inverter-duty motors [7]. Further, the aging models have been augmented to take PWM-related effects into account [10,11].

While all of these affects are present in aircraft generators and EPS, only select ones can be influenced by changing operating characteristics through an HESM. Specifically, PWM-related effects will continue to exist and might be somewhat mitigated by ensuring that voltage ripple on the distribution systems is minimized. However, transient loading can potentially have a big impact on the winding, and hence the insulation, temperature, as high peak currents significantly increase instantaneous loss in the windings.

In [11], the authors provide an experimentally validated model for polyimide insulation aging in inverter-fed machines that considers voltage magnitude (V) and temperature (T) at a given switching frequency. The expected life of such a system has been found to be

$$L = K_L e^{-aV} e^{-bT} \quad (1)$$

where $a = 0.0014$ and $b = 0.01$ (in accordance with models discussed in [5]). Note that the parameter K_L is application-dependent and can only be determined from measurements in a specific system. However, the model in Eq. (1) allows us to characterize the relative influence of voltage and temperature between operating conditions experienced in the EPS without and with a representative HESM.

Power Electronic Devices

Power electronic systems and their associated components present a major reliability concern in modern more-electric aircraft (MEA). Specifically, power electronic devices have failure rates that depend significantly on electrical, thermal, and mechanical stresses either induced directly through their operation or induced from the environment, such as vibration. While electrical stresses can be significant, it is mostly the thermal stress caused by internal heating and external ambient temperatures that causes failures within devices. Thermal cycling can introduce mechanical stress on the solder joints and bonded wires, which, after several cycles, can experience fatigue failures [12]. High temperatures themselves, introduced through higher than anticipated loss, can cause weakened solder joints, which may then be further compromised by mechanical vibration or evaporate due to increasing contact resistances. Such issues can compound with increasing integration of components into power dense packaging.

For electronic systems, reliability is determined by the summation of the expected failure rates of the individual components. The component failure rates are adjusted by stress multiplication factors that depend on the operating and environmental conditions of the individual components, such as electrical stress and temperature. The standard for reliability prediction is MIL-HDBK-217 [13], which outlines procedures and provides individual failure rates for many components that are utilized in electronic applications. However, as pointed out in [14], such detailed failure rate calculations are very cumbersome and impractical at a design stage, particularly when trading off a variety of operating conditions. Luckily, overall failure rate sensitivities of an electronic system can be predicted without detailed knowledge of the individual performance of each component. According to [14], it is sufficient to monitor electrical stress of the major devices and keep track of the average component temperature to allow reasonably accurate predictions (i.e., to within approximately 10%) of failure rates at different operating conditions.

For the failure analysis in the following sections, it is assumed that rectifier diodes are utilized with stress factors determined from calculations provided in [13] and replicated in Figure 1. (It should be noted that the basic mechanisms discussed herein are readily applicable to other power electronic device topologies as well.) Depending upon the change in operating conditions due to introduction of the HESM (adjusted loading profile in the converter), the failure rates of the power electronic devices are adjusted utilizing the stress factors. The impact of device failure rates will then be extrapolated on the reliability of a total converter system. Specifically, it can be assumed that power electronic devices are responsible for approximately 10% of all failures in a passive, six-pulse rectifier based generator control unit (GCU) and for approximately 40% in a GCU featuring active rectification [15]. Although these assumptions may not exactly match a specific system, they are representative and will provide a reference-level for the estimated impact on converter reliability by the introduction of

HESMs. For example, if a diode rectifier would operate at a junction temperature of 100°C (373 K) instead of 125°C (398 K), the temperature stress factor would reduce from 13.4 to 8.0, which is a 40% decline in the diode's failure rate. Extrapolating this result to the GCU-level, it could be expected that the GCU's reliability (i.e., mean-time before failure) would increase by 4.1%.

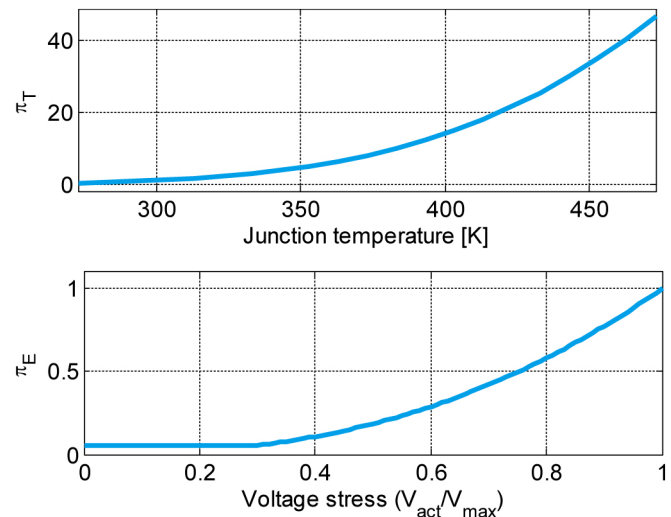


Figure 1. Failure rate stress factors for rectifier diodes: junction temperature (π_T) and blocking voltage (π_E).

Mechanical Components

All components experience mechanical stress due to temperature-induced expansion, external vibration, and internally created forces across a wide-frequency spectrum. Capturing the impact of all of the individual stresses is nearly impossible in theory and requires detailed monitoring and testing in practice, as is often done with vibration spectrum measurements for the analysis of bearing fatigue/failures [16]. However, it is possible to predict changes in the expected failure rates of certain rotating mechanical components that are due to material fatigue and changes in stress/force loading. Specifically, bearings have been analyzed in detail for different failure characteristics [17,18], and relationships for the different influences on the expected life have been established [17,19,20,21]. Further, fatigue failures due to variable loading stress on rotating members such as generator shafts has been analyzed in detail in many standard textbooks [19,22]. Thus, the focus in this investigation will be on defining the potential reduction in fatigue failures in bearings and generator shafts due to the employment of HESMs.

To evaluate material fatigue on the generator shaft and bearings, a simple example of a shaft is utilized in this paper that experiences torsional and bending loads, as shown in Figure 2. The shaft length is $L = 0.2$ m and its diameter $d = 25.4$ mm. Bearings are mounted at axial positions of 0.03 m and 0.2 m measured from the pinion, and it is assumed that the shaft interfaces with a gear box at the pinion. The shaft experiences a torsional load T created by the electromagnetic