Reliability of Radioisotope Stirling Convertor Linear Alternator

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Abstract. Onboard radioisotope power systems being developed and planned for NASA's deep-space missions would require reliable design lifetimes of up to 14 yr. Critical components and materials of Stirling convertors have been undergoing extensive testing and evaluation in support of a reliable performance for the specified life span. Of significant importance to the successful development of the Stirling convertor is the design of a lightweight and highly efficient linear alternator. Alternator performance could vary due to small deviations in the permanent magnet properties, operating temperature, and component geometries. Durability prediction and reliability of the alternator may be affected by these deviations from nominal design conditions. Therefore, it is important to evaluate the effect of these uncertainties in predicting the reliability of the linear alternator performance. This paper presents a study in which a reliability-based methodology is used to assess alternator performance. The response surface characterizing the induced open-circuit voltage performance is constructed using 3-D finite element magnetic analysis. Fast probability integration method is used to determine the probability of the desired performance and its sensitivity to the alternator design parameters.

INTRODUCTION

The NASA Glenn Research Center (GRC), the Department of Energy (DOE), Lockheed Martin and Stirling Technology Company (STC) are developing a free-piston Stirling power convertor that is being considered as an energy conversion system for future NASA space science missions. The Stirling Radioisotope Generator (SRG) is being evaluated as an alternative to the Radioisotope Thermoelectric Generators (RTGs) due to higher efficiency. It is anticipated that the higher efficiency of the SRG would reduce the amount of fuel required for an equivalent level of power as compared to RTGs by a factor of 4. GRC has been involved in the development of Stirling power conversion technology for over 25 years and is currently providing technical support to DOE and their system integration contractor for the SRG110, Lockheed Martin, at Valley Forge, PA.

The new radioisotope power system (RPS) using a Stirling Convertor Assembly (SCA) as an energy conversion device would be required to perform efficiently without failure and maintenance for up to 14 years. Therefore, high reliability is of paramount importance over the life of the mission (Shah, et al., 2003). High reliability of all the critical components of the RPS certainly assures the overall system reliability. SCA is one of the most critical components that convert the thermal energy into the electrical energy. Within SCA, there are several components of which linear alternator convert the mechanical energy into the electrical energy. Considering the role of linear alternator, its reliability is of utmost importance.

Geng et al (2001) and Niedra (2001) performed deterministic 3-Dimensional finite element analysis of the linear alternator and performed different types of tests under varying environmental conditions for the magnet and alternator to evaluate the performance. The deterministic analysis (Geng, 2001) was aimed to aid engineers in the design, development and evaluation and understanding of advanced linear alternator designs. It is well known that the design variables in any engineering designs have uncertainties due to variations in the manufacturing and fabrication process, material behavior, loads and boundary conditions. Conventional engineering design methods (deterministic) solely based on mean or nominal values of design variables provide single point estimates of the component and/or system response. In reality, the design variables governing the performance and life of the component or system have uncertainties from different sources such as manufacturing, material behavior, fabrication, environmental conditions, mission scenarios, etc. Uncertainties in the linear alternator design variables such as magnetic properties, stator and mover lamination thickness, gap between the mover and the magnets,

current, current spikes, etc. also exist. Conventional methods account for these uncertainties via safety factors and safety margins. Designs using deterministic approaches often results in highly conservative designs. The reliability-based designs account for uncertainties using their likelihood of occurrence and integrate them using probabilistic and reliability based approaches. The reliability-based design methods can formally and rationally quantify the effect of uncertainties on the component and/or system performance and in turn reliability. Furthermore, design based on deterministic approaches require performing several cost and time prohibitive tests in order to assure reliability of a given component or system.

Probabilistic analysis lends a powerful analytical tool to quantify the reliability as well as sensitivity of design variables on the alternator performance. Sensitivity can be used to guide the design process as well as improve the existing designs and develop guidelines to design limited laboratory tests required for validation and verification, quality control and inspection criteria.

The present paper describes the results of the probabilistic analysis of the SCA linear alternator and outline of the numerical simulation approach used to perform electromagnetic finite element analysis and fast probability integration (FPI).

MAGNETOSTATIC FINITE ELEMENT MODEL

The free-piston Stirling power convertor generates electrical energy at a fixed frequency using thermal energy from the heat source. The linear alternator is one of the most critical components governing the performance and durability of the power convertor. It converts energy of plunger (mover) mechanical excitation into electrical energy using magnetic strength of the permanent magnets (PM). The SCA linear alternator contains stationary magnets attached to the stator laminations. Each individual magnet produces magnetic flux perpendicular to the planes of the stator coils, which are wound around each stator legs. The rate of change in magnetic field density due to variation in mover position induces a voltage in the coil. In addition, current flowing through the coils induce additional magnetic field as well.

The magnetic flux linkage λ is a function of the mover position x, applied load current I, material properties M, and geometry G of the components and may expressed as

$$\lambda = \lambda(x, I, M, G) \tag{1}$$

Based on this, the induced voltage, V in the coils is calculated using the following equation

$$V = \frac{d\lambda}{dt} = \frac{\partial \lambda}{\partial x}\frac{dx}{dt} + \frac{\partial \lambda}{\partial I}\frac{dI}{dt} \tag{2}$$

Due to complexity of the structure, a deterministic analysis using 3-D magneto-static finite element model was performed (Geng et al., 2000, 2001). The model consisted of a quarter section of the alternator and included the following components: 1) ¼ stack of mover laminations, 2) permanent magnets, 3) ¼ stack of stator laminations, and copper half-coils. This model was used as a basis to develop a parametric linear alternator finite element model to develop performance/response surface required for probabilistic evaluation.

The model features parametric representations of permanent magnet material properties, geometrical dimensions of the mover and stator stack laminations, and operating temperatures. Symmetry boundary conditions are used for the magnetic field. Constant current sources applied to the coil terminals are used as electrical load applied to the alternator.

The material properties describe the behavior of materials when subjected to electromagnetic fields. The permanent magnets, Hyperco 50A for mover and stator laminations, and copper coils are used in the finite element model. The following relationship between the macroscopic parameters for permanent magnets is used

$$B = \mu_0(\mu_r H + M_p) \tag{3}$$

Where B, H, M_p are magnetic flux density, magnetic field strength, and spontaneous magnetization, respectively. Relative permeability, μ_r and magnetization, M_p were used in the functional representation of the demagnetization curves data for permanent magnets at various temperatures as depicted in Figure 1. The coercive force H_{ci} declines at higher temperature as well as lower temperatures. Based on the vendor supplied test data, the temperatures range of 20 ^{o}C – 90 ^{o}C has been found to be safe.
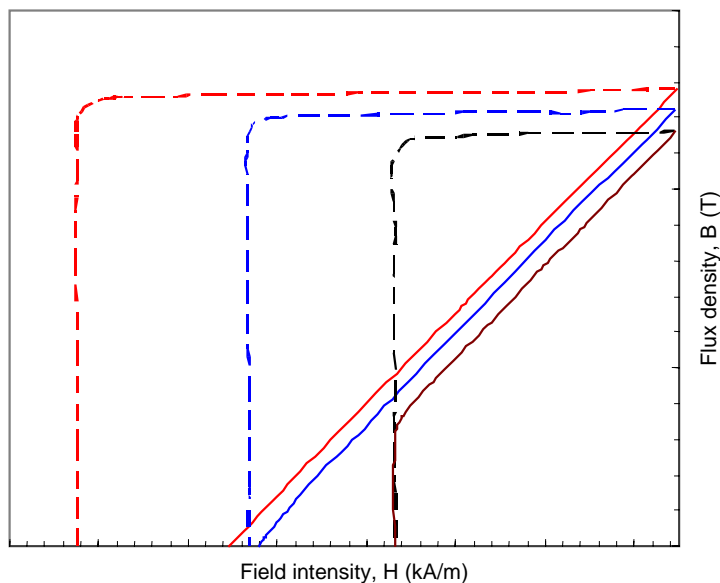
The knee in the normal induction curve shifts from third to second quadrant with increase in the temperature, which may result in the irreversible changes. To avoid irreversible loss of magnetic energy for the temperature over 100 ^{o}C, it must operate above the knee of the demagnetization curve. Other important characteristics of permanent magnets are reversible temperature coefficients of B_r and H_{ci} which are different for each other and vary depending on material. These coefficients for permanent magnets were obtained from the manufacturer.

FIGURE 1. Demagnetization Curves of Permanent Magnet at Various Temperatures.

SIMULATION OF UNCERTAINTIES

As describe before, the linear alternator is one of the most critical components governing performance and reliability of the Stirling convertor. Excessive armature reaction to off-design high temperatures, possible high armature current surges, oxidation, may result in the partial demagnetization of permanent magnets and therefore the performance and reliability of the alternator. The magnets do have uncertainties associated with their properties that affect the performance of the alternator. Additionally, the uncertainties associated with the geometry of the stator lamination assembly, the mover, the gap between mover and the magnet, etc. affect the performance of the alternator and ultimately the power output. The alternator magnets are generally designed to operate in the temperature range and current amplitudes far away from the onset of demagnetization. However, temperature excursions may occur if sensor/controls malfunction or fail. Also, current spikes may occur during the mission. These abnormal conditions could partially or fully demagnetize the magnets. The current spikes may be the results of some induced voltage spike due to controller malfunction or inductive load switching (such as motor or actuator).

The following approach has been adopted to simulate the effect of uncertainties in the alternator performance and reliability quantification. This approach involves the following steps:

1. Identification of design variables and associated uncertainties affecting the linear alternator performance.
2. Computation of the corresponding response functions defining the deterministic relationship between the design random variables and alternator performance at different real flight conditions.
3. Application of probabilistic analysis tools to compute probability density functions (PDF) and/or the cumulative distribution functions (CDF) and sensitivities of the responses.
4. Quantification and prediction of the alternator reliability for different mission profiles.

The presented probabilistic analysis includes uncertainties in the fabrication, material properties and environmental conditions. The scatter in design variables is based on the allowable tolerances and engineering judgment. The maximum and minimum tolerances have been assumed to correspond to ±3 standard deviation. A list of random design variables, their coefficients of variations and distributions is given in Table 1. Air gap value and corresponding variation were calculated based on mover, stator and magnet's dimensions and tolerances specified in the design drawings. It is clear that air gap and temperature are the most uncertain variables.

TABLE 1. Linear Alternator Design Random Variables.

Random variable	Mean Value	Coefficient of Variation, %	Probability Distribution
Relative permeability μ_r	-	0.83	Weibull
Magnetization, Mp (kA/m)	-	1.67	Weibull
Intrinsic coercivity, H_{ci} (kA/m)	-	1.67	Lognormal
Mover stack lamination thickness (mm)	-	0.412	Normal
Mover outside radius (mm)	-	0.041	Normal
Stator stack lamination thickness (mm)	-	0.206	Normal
Stator inside radius (mm)	-	0.101	Normal
Air gap between mover and magnets (mm)	-	5.12	Normal
Temperature (^{o}C)	75	6.67	Normal

The primary parameters of interest for reliability evaluation are the magnetic field parallel to the axes of the coil windings and maximum magnetic field intensity *H*. The model was set-up to calculate an average magnetic flux crossing the hypothetical cut-planes that were defined along the axes of the coils.

A probabilistic integration of the finite element analyses results has been performed. The cumulative distribution function (CDF) of the permanent magnet induced voltage and the sensitivity factors were computed. Figure 2 shows the cumulative distribution function of the open-circuit voltage and Figure 3 shows its sensitivity to the random variables. The scatter range in the voltage is 75-86 V. The air gap size, magnetization of the permanent magnet,
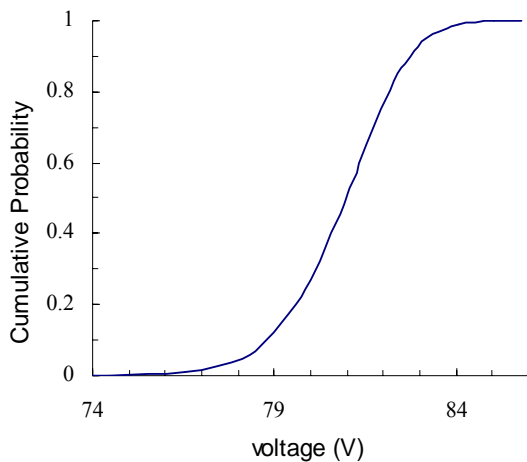

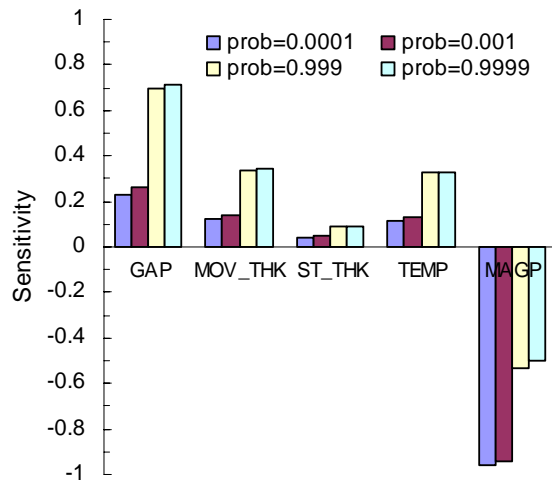**FIGURE 2.** Cumulative Distribution Function of Voltage.

FIGURE 3. Sensitivity of Voltage to Design Variables.

mover stack thickness, and environmental temperature are the most significant variables to the scatter in the voltage. The variable sensitivity shows that magnetization dominates at the low probability level, whereas the air gap dominates at the higher probability level. Since a smaller gap is required to generate higher voltage, intuitively also one could say the uncertainties in the air gap would be more sensitive to the higher voltage levels. Therefore, the uncertainties in the gap should be minimized to assure reliability for higher voltage levels. Intuitively, uncertainties in the component or response depend on coefficients of variation and the distribution function types of the design variables. Since sufficient data for design variables related to magnet properties is not available, study showing the effect of variation in the design variable uncertainties would add value to the reliability prediction. Therefore, additional analyses showing the effect of variation in the uncertainties of the air gap and magnetization was performed. Results of these analyses showing the impact of uncertainties variation on the open-circuit voltage at 0.001 (lower tail) and 0.999 (upper tail) probability levels are given in Table 2.

TABLE 2. Dependence of Voltage on Coefficient of Variation.

Coefficient of Variation, %		Voltage (V)	
		0.001 Probability	0.999 Probability
Gap	3.1	74.7	84.4
	5.12	74.5	85.0
	7	74.2	85.8
Mp	0.8	76.9	84.3
	1.67	74.5	85.0
	3.0	70.3	86.5

Additionally, the effect of the different probability distribution functions for the relative permeability and magnetization on voltage is shown in Figure 4. Results show that the change in the distribution type from Weibull to lognormal has insignificant effect on mean value and standard deviation for the voltage. However, in case of the Weibull distribution the median and mean values do not coincide thereby showing skewness in probabilistic density function, which may affect the reliability of voltage. In the case of lognormal distribution the mean and median
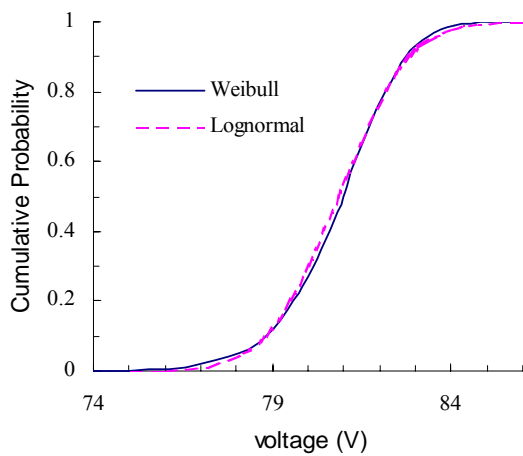

FIGURE 4. Cumulative Distribution Function of Voltage for Different Distribution Functions.
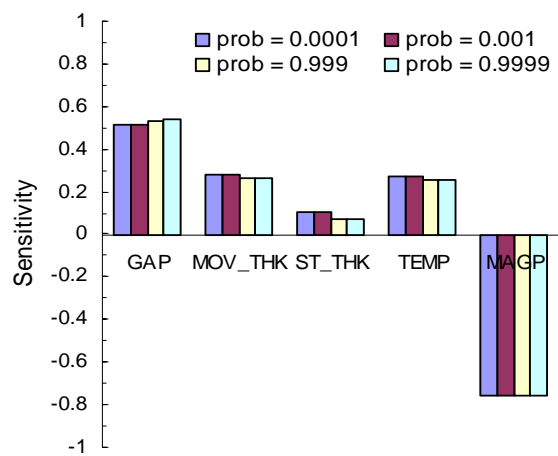
FIGURE 5. Sensitivity of Voltage to Design Variables (Lognormal Distribution).

values coincide but the sensitivity to the design variables remain same at 0.001 and 0.999 cumulative probability levels, Figure 5. Also, the air gap and magnetization are less sensitive to the voltage as compared to those for the Weibull distribution.

V. FUTURE WORK

The probabilistic analysis and results reported here is a first step in the reliability evaluation of the Stirling engine alternator. The most important variables due to fabrication and material properties influencing the alternator performance were presented. However, the alternator performance may degrade with time due to possible material degradation and environmental conditions. The permanent magnet demagnetization due to elevated temperature, possible current spikes and surface oxidation is of great importance since it can reduce intrinsic magnet coercivity (magnet strength). Figure 6 shows the variation of magnet strength versus temperature for the permanent magnets. It shows that the rate at which FEA calculated field intensity degrades with respect to temperature is much lower than the rate at which magnet strength degrades. Also, the extrapolation of the curves in Figure 6 show that the magnet strength will exceed the calculated field intensity at some temperature and result in failure (demagnetization). In probabilistic sense the magnet strength and calculated field intensity are uncertain and therefore there is probability of failure even at lower temperature. Therefore, a further study on reliability using the magnet strength, calculated field intensity/induced voltage/power is planned for future study.

Currently, NASA GRC is conducting experiments that will help establish the magnet strength degradation. Although it is understood that permanent magnet material properties are among those that control the power output, additional parameters may control the power as well. Combined simulation based on finite element analysis, equivalent circuit modeling, and probabilistic analysis tools and experimental data will provide a better reliability model for the Stirling power convertors.
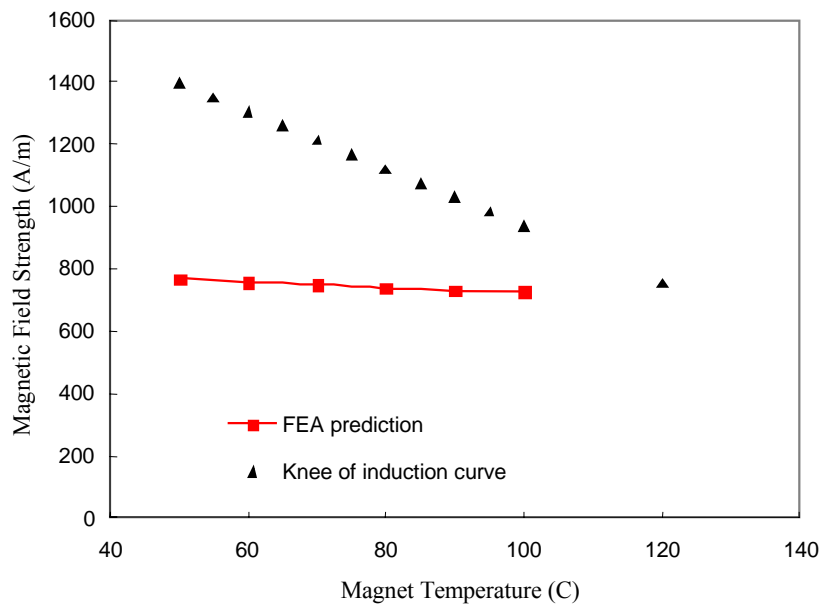

FIGURE 6. Sensitivity of Resistance to Demagnetization.

CONCLUSIONS

Uncertainties associated with the design variables of the Stirling Convertor linear alternator have been identified and its effect on the linear alternator performance has been quantified. A probabilistic evaluation of the linear alternator open circuit induced voltage has been performed and its cumulative probability distribution function has been

computed. Also, the sensitivity of the design random variables has been quantified. The results show that the induced voltage range from 74 – 86 V and the air gap between the mover and the magnets is most sensitive to the high voltage levels whereas the magnetization dominates the low voltage levels. In order to understand the effect of uncertainties due to the lack of sufficient test data, a parametric evaluation on the scatter in significant variables and distribution types has been performed. Results indicate that the lognormal distribution for the air gap and magnetization is less sensitive to voltage at all levels than the Weibull distribution. Also, the resulting distribution of voltage is more skewed due to the Weibull distribution of the air gap and magnetization than that due to lognormal distribution. The reliability of the performance is affected more due to skew distributions. Also, future work on the Stirling Convertor Assembly linear alternator reliability has been described. The reported analysis and the results lays a good ground work for the further reliability analysis that includes the aging effect and computes the reliability of available power during the mission.

NOMENCLATURE

μ_0	=	permeability (H/m)
μ_r	=	relative permeability
B	=	flux density (T)
H	=	magnetic field intensity (kA/m)
t	=	time (s)
x	=	mover position (mm)
λ	=	magnetic flux linking coil (Wb)
GAP	=	air gap between mover and magnets (mm)
MOV_THK	=	mover stack laminations thickness (mm)
ST_THK	=	stator laminations thickness (mm)
TEMP	=	temperature (^{o}C)
MAGP	=	magnetization (kA/m)

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13. ABSTRACT (Maximum 200 words)

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