Study on the reliability evaluation method for sun-synchronous orbit satellite power subsystem

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Abstract. As an important component to provide satellite energy, the power subsystem in-service operation state is of great significance to satellite safety. In this paper, the power subsystem reliability evaluation is carried out on the basis of the actual telemetry data from satellites. Firstly, the influence factors of the power subsystem telemetry data are analyzed, and the modified method to calculate the output parameters is established; Furthermore, the degradation trajectory of the power subsystem output power is analyzed under different in-service time, and then the difference between the global and the local degradation is discussed. Finally, using the performance degradation model, the reliability evaluation method for the power subsystem is set up. The result shows that the local degradation trajectory in the end of lifetime is critical for the remaining useful life prediction, and the method can provide references for the in-service reliability analysis of the on-orbit satellites.

1. Introduction
With the increase of the in-service time, the on-orbit satellites power subsystem performance degrades gradually, and its efficiency decreases. To ensure the satellites’ power supply safety, it is necessary to assess the reliability of the on-orbit satellites’ power subsystem in-service state and then to predict the remaining useful life reasonably. From now on, lots of research work from the domestic and foreign scientists has been carried out in the field of performance degradation model. The regression analysis model, the time series model, the degradation path model and the typical stochastic process model (such as Weiner model, Gamma model, Poisson process, etc.) are proposed\cite{1-9}. In a word, the current research, focusing on the performance degradation, can be divided into two parts: one is based on the testing method. The samples’ degradation trajectories and characters are determined by the accelerated test in laboratory. The other is based on the sampling method. The possible degradation trend for some products is deduced by the theoretical analysis, and then the reliability model is validated by the minimum sampling assessment. Therefore, the reliability evaluation method based on performance degradation has become an important tool to calculate the reliability for the products during their in-service time. In the existing literature, the global degradation method is often used\cite{4-6}. Namely, the method is to fit the performance degradation trajectory for the whole usage life. Yet, there are some other scholars to make use of the method by fitting the time-scale transformation for the degradation trajectory\cite{7-8}. Only a small amount of literature has been carried out with segmentation.
degradation method[9] to evaluate the reliability. As a matter of fact, the degradation trajectory for some products in different in-service stages is completely different. There is great deviation between the fitting degradation trajectory and the actual usage for some products’ whole life. Therefore, this paper focuses on the performance degradation from some sun synchronous orbit satellites’ power subsystem telemetry data. Firstly, a modified method for the power subsystem output parameters is established. Further, the degradation trajectory for the output power is analyzed. In the end, the reliability evaluation method for the output power is set up by using the performance degradation model.

2. The modified method for the power subsystem output parameters

The factors, such as the angle between the satellite orbital plane and the sun rays, the distance between the satellite and the sun, may change along with the satellite on-orbit time. Therefore, the output parameters for the power subsystem also change dynamically. In order to eliminate the interference from the external factors to ensure the calculation benchmark accuracy, a modified method for the solar array output parameters is proposed.

2.1. The modified method for solar effective intensity factor

For the sun-synchronous orbit satellites, the solar cell array output parameters are mainly affected by the angle between the solar array and sunlight incidence, the distance between sun and satellites. So the solar effective ray intensity factor, can be written as[10]

\[ K_s = \cos \beta \times K_d \] (1)

In equation 1, \( \beta \) is the angle between the sun and the solar array normal; \( \beta = \gamma - \alpha \), \( \gamma \) is the angle between the sun and the satellite orbital plane; \( \alpha \) is the angle between the battery array and the orbital plane; \( K_d \) is the distance factor, \( K_d = 1/d^2 \), d is the distance between sun and earth.

The modified distance between sun and earth within the orbital period can be calculated with equation 2.

\[
d(t) = \begin{cases} 
  d - R \cdot \left( \frac{\varphi_0 + \omega t}{2\pi} \right) \cdot \sin \left( \frac{i + \Theta - 90}{2\pi} \right) & 0 \leq \varphi_0 + \omega t < 180 \\
  d - R \cdot \left( 1 - \frac{\varphi_0 + \omega t}{2\pi} \right) \cdot \sin \left( \frac{i + \Theta - 90}{2\pi} \right) & 180 \leq \varphi_0 + \omega t < 360 
\end{cases}
\]

(2)

In equation 2, \( R \) is the summation of the earth radius and the satellite orbit height; \( \varphi_0 \) is the satellite referred fiducial angle; \( \omega \) is the earth rotation speed; \( \Theta \) is the angle between the zodiac and the equator; \( i \) is the orbit inclination.

2.2. Earth shadow modification

For the sun synchronous orbit, the earth shadow factor can be written as

\[ K_e = \frac{1}{180} \cdot \cos^{-1} \left[ \sqrt{1 - r_e^2 / (r_e + h)^2} \right] \cdot \cos \gamma \] (3)

In equation 3, \( r_e \) is the earth equatorial radius; \( h \) is the satellite orbit height. If there is a star eclipse during the loop and \( 0 \leq K_e < 1 \), the earth shadow duration time is \( T_e = T_0 \times K_e \), \( T_0 \) is the satellite orbital period.

2.3. Comprehensive modification
Because the satellites solar array output parameters is different, a comprehensive modification $Y_m$ for the solar cell array can be calculated by using equation 4.

$$Y_m = \frac{Y_{out} \times K_e \times K_y}{Y_{max}}$$

(4)

In equation 4, $Y_{out}$ is the actual output for the solar cell array; $Y_{max}$ is the maximum output value.

The original and modified telemetry data (the bus current) for some sun-synchronous orbit satellite are shown in figure 1.

Similarly, the bus voltage can also be corrected by this method. Therefore, the modified output power for the solar cell array can be written as

$$P_m = U_m \times I_m$$

(5)

In equation 5, $P_m$ is the modified output power; $U_m$ is the modified output voltage, $I_m$ is the modified output current.

3. The output power performance deregulation trajectory analysis

3.1. Reliability analysis for the global deregulation

With the increase of the in-service time, the output power gradually decreases. At present, the performance degradation curve is commonly linear, exponential, logarithmic, etc[11]. So, in this paper, the same series solar synchronous orbit satellites are selected to calculate the output power deregulation trajectory at a given time. Because these selected satellites’ output power also does not come to the designed life, the reliability index for the power subsystem in the satellite design source is referred, and the output power output value decreases to 90% rating max output value as the limit (the pseudo life). Then the pseudo life is obtained by using the two kinds of trajectories. The deregulation curves are filled into table 1.

| type       | deregulation curve       | confidence | type       | deregulation curve       | confidence |
|------------|--------------------------|------------|------------|--------------------------|------------|
| exponential | $y = 1 - 0.0228 \times e^{-9.140t}$ | 0.955      | exponential | $y = 1 - 0.0083 \times t$   | 0.979      |
|            | $y = 1 - 0.0198 \times e^{-9.041t}$ | 0.946      | linear     | $y = 1 - 0.0077 \times t$   | 0.982      |
|            | $y = 1 - 0.0213 \times e^{-9.089t}$ | 0.981      |            | $y = 1 - 0.0069 \times t$   | 0.991      |

Figure 1. The original and modified bus current.
Furthermore, the pseudo life is assumed to obey the normal distribution, shown in figure 2. The output power reliability under the normal distribution can be calculated with equation 6.

\[ R(t) = 1 - \Phi \left( \frac{t - \mu}{\sigma} \right) \]  

(6)

According to equation 6, for normal distribution, \( \hat{\mu} = 13.35 \), \( \hat{\sigma} = 0.925 \), the pseudo calendar life is 14.535 years until the output power output value decreased to 90% rating.

![Figure 2. The pseudo life normal distribution.](image)

### 3.2. Reliability analysis for the local degradation

According to the actual in-service data, the output power output deregulation trajectories are not always linear or exponential. The performance degradation curve is not same at different in-service stages.

Table 2 shows that the fitted output power deregulation trajectory at different stages based on figure 3.

| Stage | curve | In-service time/year | Confidence |
|-------|-------|----------------------|------------|
| 1     | \( y_1 = 1 - 0.0082 \times t \) | [0, 6] | 0.977 |
| 2     | \( y_2 = 0.9508 \times e^{-0.007} \) | [6, 9.5] | 0.981 |
| 3     | \( y_3 = 0.936 - 0.0029 \times t \) | [9.5, 11.4] | 0.980 |

Similarly, the pseudo calendar life is 13.688 (normal distribution) years until the output power value decreases to 90% rating.

The output power reliability curve, along with the in-service time increases, is calculated if the pseudo life is obeyed to normal distribution under the global (blue line) and local deregulation (red line), shown in figure 3.
Through the above calculation and figure 3, the calendar life determined by the local deregulation is shorter 6.97% than the global deregulation. Though the former life is rather conservative, it is safer than the latter.

![Figure 3. The reliability curve for the output power.](image)

In a word, while the output parameters reliability for the power subsystem are analyzed, the following points should be paid attention to: 1) the segment duration for the deregulation trajectory at different on-orbit time; 2) the influence factors for the output parameters while the degradation trajectory is adjusted during in-service time; 3) the performance degradation trajectory in the end of lifetime, which is the key factor to affect the power subsystem reliability.

Since these satellites do not come to their designed life, their degradation trajectories (or the pseudo life) may not consist with the actual situation. Therefore, it is necessary to focus on the process of the local degradation to get the accurate life in future. That is to say, how to analyze the degradation trajectory in the remaining useful life to calculate a more reasonable distribution for the pseudo life, is an important job to analyze the satellite on-orbit life for the further study.

4. Conclusions
(1) A modified method for the power subsystem output parameters of the sun synchronous orbit satellite is established by considering the following factors, such as the angle between the solar cell array and solar light, the distance between the satellite and sun, etc.

(2) The output power performance under the global and local degradation trajectory is analyzed, and the pseudo life and its normal distribution parameters are calculated.

(3) The output power reliability under the global and local degradation trajectory is analyzed, and the calendar life determined by the local deregulation is shorter 6.97% (normal distribution) than the global deregulation. The life from the local degradation is more conservative and safer than the global.

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