Research of A Method of Satellite Power Component Degradation Estimation based on Clustering

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Abstract. For satellite on-orbit supply unit during the period of degradation problems, based on the factors that affect supply unit output power and accepted by the satellite ground stations to related telemetry data, this paper proposes a clustering-based satellite solar power components regression estimation method. By clustering method to find a place to supply unit power generation with the working conditions, according to the influence factors of power supply components, we conduct clustering and then directly fitting attenuation of the battery, and we make the periodic fitting analysis for periodic influence factors of solar cell array. Finally, we have established the model of periodic compensation and output power degradation estimation, and carried out the attenuation estimation is carried out according to the actual engineering data. The proposed method is used to evaluate the attenuation of the solar array of an on-orbit resource satellite. This method overcomes the shortcoming that the existing method must rely on long-term data to carry out attenuation evaluation. It can be applied to the auxiliary decision-making of the health state management of the power supply system of on-orbit satellites, and has important reference value for providing the operational benefit of satellites.

Keywords: Satellite power unit; clustering; cycle recognition; estimation of degradation.

1. Introduction

As more and more satellites have been launched into space, the stability and reliability of satellites are becoming the focus of the researchers. Among the satellite subsystems, the power subsystem is the subsystem that has the most significant influence on its on-orbit life. In the process of satellite operation in outer space, the power subsystem provides power for it[1,2]. When the satellite is running in the illumination area, it is powered by the solar cell array in the power subsystem and charged by the battery pack[3]. In the shadow zone, the battery provides energy for the satellite[4]. In general, the satellite power subsystem is mainly powered by solar cell array and battery pack, so it is necessary to evaluate the state and estimate the degradation of solar cell array and battery pack.

However, different working states will lead to different output powers, when the satellite is running in space. Therefore, in order to accurately evaluate the degradation of various components of the power system, it is necessary to ensure that the degradation characteristic parameters selected during the evaluation are as consistent as possible. When solar arrays work in space, the factors affecting the output power of solar cells array can be summarized as follows:

1. Operating temperature.
2. Solar intensity.
3. Space environment, such as particle irradiation and ultraviolet irradiation[5,6,7,8].

The first two are mainly periodic changes, and the third is a long-term attenuation change, which has a great impact on the life of the satellite. Battery degradation is mainly reflected in its capacity change. With the increase of charge and discharge cycle times, its actual capacity will decrease. Battery capacity degradation can be divided into internal and external aspects. ①Internal degradation of the battery: dissolution of positive electrode materials and self-discharge process of the battery;

②External complex environment: solar particle storms, damage caused by cosmic rays and linkage effects caused by other subsystem anomalies [9,10].

Therefore, it is not hard to see that the satellite's power subsystem is affected and tested by various factors in the complex space environment. Once the power subsystem fails to provide sufficient capacity, the satellite will not be able to continue to complete the task in space or even collapse. At present, the degradation assessment methods for power supply components are mainly model-based and data-driven[11,12]. The traditional modeling method is based on the internal physical and chemical characteristics of power supply components to build the model and simulate its degradation process. The satellite power subsystem mainly consists of solar cell array and battery. There are two main types of modeling methods for solar cell arrays, including the equivalent flux method from the Jet Propulsion Laboratory (JPL) and the displacement damage method from the United States Naval Research Laboratory (NRL)[13]. Method for battery model mainly includes: electrochemical analysis, Ann method and impedance method to evaluate battery capacity degradation[14]. With the continuous progress of artificial intelligence and machine learning, the methods of satellite power component degradation assessment based on data drive are increasing gradually[15]. Data driven method is needed to pay attention to the power supply unit inside the degradation mechanism of complex, only from the perspective of satellite telemetry data transmission to the ground, with the help of a machine learning algorithm to study of historical data, through the trained model to evaluate degradation situation of the power components, this method not only get rid of the research on the power part of the internal mechanism of complex, at the same time for different working conditions and equipment supply unit has a strong applicability.

In this paper, we propose a method of power component degradation estimation based on clustering. Firstly, relevant parameters affecting the power output of power components and degradation characteristics characterizing the degradation of power output performance are extracted. Clustering is carried out according to the extracted relevant influence parameters, and we could obtain the same output working condition points which can be considered consistent with the working state. Then analyze the degradation characteristics of the change. If there is a periodic change caused by the change of satellite orbit, we will use a polynomial to fit the periodicity of the degradation feature, and make periodic compensation for the degradation feature value of the same working state after clustering. After eliminating the periodicity, the on-orbit attenuation estimates of the satellite power components can be obtained by fitting the data. This method can estimate the real time attenuation of satellite data in orbit over a period of time. It can be used not only to analyze the working state of power supply components in the initial stage of satellite launch, but also to estimate the service life and working life of power supply components in the late stage of satellite operation, providing a basis for the on-orbit health state management of power supply components.

2. Power Component Attenuation Evaluation Method based on Clustering

2.1 Working Principle of Solar Cell Array

The work of this paper is based on a low-orbit sun-synchronous orbit satellite in orbit, whose solar cell array guarantees the operation of the load satellite during the illumination period and recharges the battery during the shadow period. Because the satellite adopts the control mode of locally-linear-sequent shunt regulation to ensure the stable bus voltage, the output voltage of the solar cell array of the satellite is composed of three parts[16], including the bus voltage of the load satellite, the average voltage drop of the cables from the solar cell array to the bus path, and the voltage drop of the isolation diode. By querying on-orbit data, the annual variation of the satellite bus voltage is within 0.8V. The isolation diode voltage drop and the average voltage drop are fixed values. Therefore, the output voltage is a fixed value, and the output current is instead selected as the parameter for modelling the performance degradation of the solar cells. Therefore, the output power of solar cell array can be represented by the output current of solar cell array under the shunt regulation control mode of the power supply system.

The output power of solar cell array is generally represented by the output current I of solar cell array[17,18]

$$I = F \cdot F_S \cdot [I_{BOL} + \beta(T - 25)] \cdot \cos\varphi$$

Here, I_{BOL} represents the output current of solar cell array when the work temperature is at 25℃ in early life and unit distance between sun and earth is 0 ° , and the unit is A. β is current temperature coefficient, and the unit is A/℃. φ is the angle of incidence, and the unit is °. F is power factor, which is dimensionless. F_S is sun-earth distance factor, which is dimensionless.

2.2 Working Principle of Solar Cell Array

The material of the satellite battery in this paper is nickel-cadmium (cd-ni) battery, which is made of sponge metal cadmium (CD) as negative electrode and nickel oxide (NiOOH) as positive electrode. The active metal hydroxide aqueous solution is the alkaline chemical battery of electrolyte. Its charge and discharge reaction can be expressed as follows:

$$\text{Negative Electrode}\ \ Cd + 2OH^- \underset{charge}{\overset{discharge}{\Longleftrightarrow}} Cd(OH)_2 + 2e^-$$

$$\text{Positive Electrode}\ \ 2NiOOH + 2H_2O + 2e^- \underset{charge}{\overset{discharge}{\Longleftrightarrow}} 2Ni(OH)_2 + 2H^-$$

$$\text{General Reaction}\ \ 2NiOOH + Cd{+}2H_2O \underset{charge}{\overset{discharge}{\Longleftrightarrow}} 2Ni(OH)_2 + Cd(OH)_2$$

For security reasons, to prevent the loss of electrolyte and sheet properties of premature decay because of nickel cadmium battery in the process of charging excessive electricity to produce gas, satellite power system battery charge controller generally allow the battery to maximum rate charging, until a gas is produced and then the charge rate decreases to a trickle charge rate. So that the battery can smoothly reach full charged state. However, as the on-orbit time of the satellite increases, under the influence of internal factors such as the dissolution of positive electrode materials, the formation of interface film and external factors such as space ion irradiation, the cut-off voltage of battery discharge cycle in the same working state and task will decrease with the attenuation of the battery.

2.3 Attenuation Assessment Process

The satellite power supply components are mainly composed of solar cell array and battery group. However, since solar cell array converts solar energy into electric energy and stores it, its degradation characteristics also have periodic changes with satellite orbit changes, while the battery does not contain such periodic changes. The step proposed in this paper, which is the application of clustering based satellite power component analysis method in solar cell array and is needed to add periodic variation of degradation characteristics, is more complex than batteries. Therefore, the following solar cell array is taken as an example to show the attenuation evaluation process.

Attenuation assessment process is shown in figure 1. Firstly, cluster parameter selection and data extraction are carried out, and then they are divided into two aspects. On the one hand, it is necessary to analyze the correlation of factors affecting the output current of solar cell array. Appropriate parameters are selected for clustering, so as to obtain the output current of solar array in the same power generation condition, which is influenced by temperature, solar incidence angle, sun-earth distance factor[19,20,21], etc.

On the other hand, during the generation process of solar cell array, it will also be affected by periodic change factors such as satellite orbit change, solar activity intensity and earth reflection. After the peak current of solar cell array is obtained as the degradation characteristic, the peak current of solar cell array is selected to fit the formula of periodic change of solar cell array with time, and then the peak current of periodic wave of each solar cell array can be obtained. We make the difference between it and the average peak current of solar cell array to get the compensation value of the output current at the corresponding time. After k-means clustering, by the time corresponding to the total output current of solar cell array in each category, the current compensation value between the total output current of solar cell array and the corresponding time is calculated. Then we get the output current of the same power generation condition, periodic variation factors such as satellite orbit, distance between the sun and the earth.

At this time, attenuation fitting is carried out for the obtained output current to obtain attenuation estimation of solar cell array output power. Specific steps are as follows:

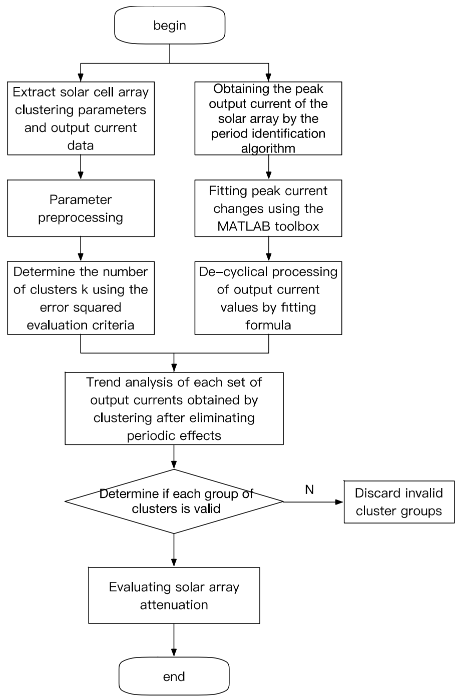

Fig. 1 Attenuation evaluation method flow

2.3.1 Parameter Acquisition and Processing

Several factors affecting the output current of solar cell array have been introduced, including temperature, solar incidence Angle, sun-earth distance factor and attenuation factor. Relevant parameters were extracted from the telemetry data, which is transmitted from the satellite to the ground, and we analyzed for the correlation with the output current of solar cell array. The parameters were processed as follows:

Temperature. Extract the outer and inner temperature of solar array panel and the outer and inner temperature of satellite shell. Through correlation analysis of more than 2300 parameters in solar cell array output current and telemetry data, the correlation degree of outboard temperature and inboard temperature of the solar panel are 0.7251 and 0.2625 respectively, and the correlation degree of outer shell temperature and inner shell temperature are 0.5992 and 0.5674 respectively. Two new mixing temperature parameters are constructed after pretreatment of the four parameters as follows:

$$T_{windsurfing} = (0.7251 \times t_{\text{out}} + 0.2625 \times t_{\text{in}})/(0.7251 + 0.2625) \quad (1)$$

$$T_{shell} = (0.5992 \times t_1 + 0.5674 \times t_2)/(0.5992 + 0.5674) \quad (2)$$

Sun-earth distance factor. Select the solar radiation factor parameters in the satellite telemetry data, and their correlation degrees are 0.4465 and 0.2964, respectively. Similarly, construct a mixed radiation parameter after the pretreatment of the two radiation factors.

$$radiation = (0.4465 \times r_1 + 0.2964 \times r_2)/(0.4465 + 0.2964) \quad (3)$$

2.3.2 Selection of the Cluster Number

How to make k-means clustering work better and get better results depends on the clustering number k at the initialization time. Here we use a simple indicator sum of squared error (SSE) to determine the optimal number of clusters.

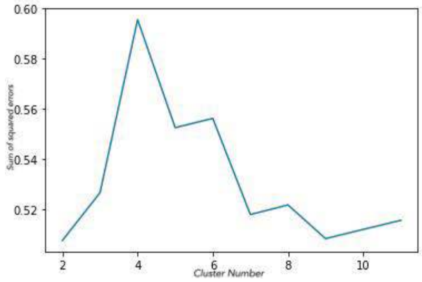

Fig. 2 SSE evaluation criteria result

As the number of clustering increases, the number of each category becomes smaller and closer. Therefore, the value of WSS (within groups sum of squares) decreases as the number of clustering increases. The optimal k value depends on the change of slope. The point where the slope changes suddenly before and after is called "knee point", and this knee point is the optimal number of clustering, and it can be found from the figure above that when k=9. At the same time, when k=9, WSS is the minimum. So k=9 is the most suitable clustering number for clustering data.

2.3.3 Period Recognition Algorithm based on Forward Distance

Although the output power of solar cell array can be expressed by the output current, the output current value fluctuates greatly. Therefore, it is necessary to extract typical characteristics from the current output current for analysis. Xu used the peak daily output power as the degradation feature to characterize the variation of solar cell array energy. In this paper, we use a forward distance-based periodic recognition algorithm and extract the peak value of each cycle of the output current as a degradation feature to analyze the periodic fluctuation of solar cell array. The flow chart of this periodic algorithm is as follows:

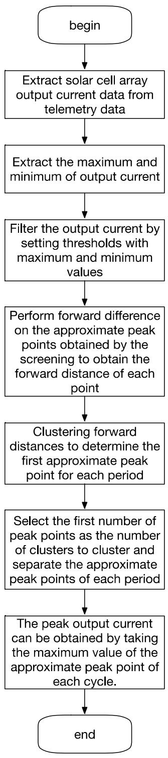

Fig. 3 Cycle identification algorithm flow chart

The steps are as follows:

(1) Extract the output current data of solar cell array.

(2) Set the threshold range of the approximate wave peak point by the maximum and minimum output current values. It is set as the value of the maximum current greater than 0.9 times. Then filter the output current value to obtain the approximate wave peak value.

(3) Each output current has a label value corresponding to it. The screened approximate wave peak points are differentiated forward through its label value. The forward distance between points in the same period is 1, and the forward distance between points in different periods is a large number. Through a clustering (k=2), the first wave-like peak of each cycle is determined.

(4) Find the first approximate wave peak as the clustering center, and take the number of the first approximate wave peak as the clustering number for the second clustering, to obtain all approximate wave peaks within each period. Then the maximum value is taken as the wave peak of each period.

2.3.4 Periocic Compensation for Current

After the peak current is extracted by the period identification algorithm, the peak current data as shown in the figure is obtained. By consulting the relevant literature, it is known that a trigonometric function can be used to fit its periodic variation. Therefore, here we use the MATLAB CURVE FITTING toolbox to fit the extracted peak current. Considering that if the complexity is too high, it will lead to over-fitting. Therefore, we select the second-order trigonometric function to obtain the theoretical current of solar cell array as a function of time:

$$I_{peak} = a_0 + a_1 \cdot \cos(\omega x) + b_1 \cdot \sin(\omega x) + a_2 \cdot \cos(2\omega x) + b_2 \cdot \sin(2\omega x) \tag{4}$$

The value of each parameter in the above solar array formula are: a_0=24.16, a_1=0.3011, b_1=-0.382, a_2=-0.09336, b_2=-0.4058, w=0.01705, and the fitting results are shown in the following figure:

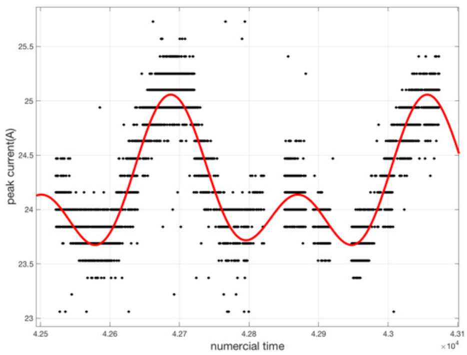

Fig. 4 Periodic fitting of output current of solar cell array

According to the function, we can get the theoretical value of the power supply current period corresponding to each time. Then make difference with the average value of the battery array current, we can obtain a periodic compensation value corresponding to each time. By making a difference between the clustered current and the periodic compensation value, the current value that eliminates the periodic influence can be obtained. The current value after clustering not only ensures the same state of temperature, solar incident angle and solar-ratio distance, but also eliminates the periodic influence of satellite orbit change and solar illumination fluctuation. Thus it can truly reflect the attenuation of solar cell array’s output power.

3. Results Analysis

In the SSE evaluation standard graph, k=3 is selected for clustering and we can get three groups of data. After periodic compensation, some data are obtained as shown in the following table:

Table 1. The raw data of clustering

Time	Current value	Cluster group	Periodic current theoretical value	Average current	Periodic current compensation value	Remove periodic current value
2016-06-01 00:00:15	24.16	3	24.06935517	24.27	-0.200644826	24.36064483
2016-06-01 00:03:45	23.69	0	24.06934624	24.27	-0.200653755	23.89065376
2016-06-01 00:05:30	23.37	0	24.06934178	24.27	-0.200658221	23.57065822
2016-06-01 00:09:00	22.9	0	24.06933285	24.27	-0.200667153	23.10066715
2016-06-01 00:45:42	21.96	5	24.06923908	24.27	-0.200760923	22.16076092
2016-06-01 00:47:27	22.43	5	24.0692346	24.27	-0.2007654	22.6307654
2016-06-01 00:52:41	23.84	2	24.06922121	24.27	-0.200778789	24.04077879
2016-06-01 00:54:26	24.16	2	24.06921673	24.27	-0.200783267	24.36078327

Taking the time of the same type of points after clustering as the X-axis, the current value after the period compensation is the Y-axis, and robust fitting is performed using the curve fitting of Matlab. Finally the result is shown in Fig. 5:

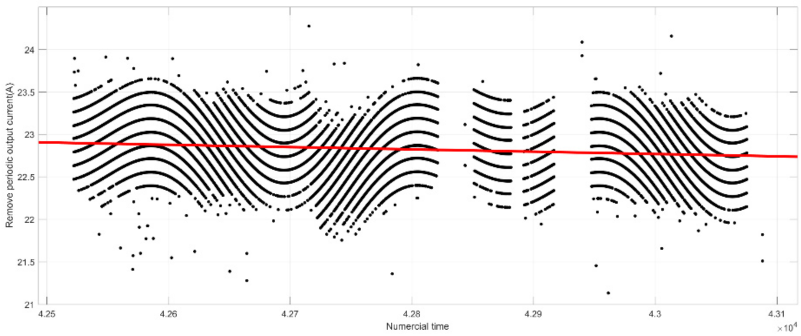

Fig. 5 Attenuation fitting is carried out for the same state point after periodic compensation

When fitting attenuation, it is observed that the effect of clustering is good, and the output current at the same state point has a steady downward trend. Therefore, we choose the straight line fitting. After attenuation fitting of the four groups of same state points after clustering, we can get the formula for the relationship between the output current and time of the four groups of solar cell array, as shown in the fitting formula term in table 2. The formula for calculating the attenuation is as follows:

$$\text{attenuation}(\%) = \frac{\text{the slope of the fitting formula} \times \text{time}}{\text{initial output current}} \tag{5}$$

It is obtained that the annual attenuation rate of satellite solar cell array is 0.433% which conforms to the engineering design. And satellite power components of battery discharge cut-off voltage degradation assessment are used as the degradation characteristics. Current, temperature and discharge depth are selected as clustering parameters. After clustering, the same operating condition point is obtained. Because the output power of the battery is not affected by the periodic changes of solar illumination and satellite orbit, the attenuation fitting can be carried out without periodic compensation.

Table 2. Evaluation results of solar array attenuation

Group	Data	Percentage	Fitting formula	(16.6.1-17.12.31) Attenuation %	Theoretical annual decay %
1	28751	0.170	y=-0.0002254x+32.87	0.55	0.353
2	36731	0.218	y=-0.0003262x+37.26	0.79	0.509
3	23570	0.140	y=-0.0001944x+31.99	0.47	0.299
4	12505	0.074	y=-0.0004475x+41.53	1.13	0.726
5	49275	0.292	y=-0.0002708x+34.41	0.67	0.432
6	17897	0.106	y=-0.0002384x+32.75	0.60	0.385
Summary	168734			0.674	0.433

4. Conclusion

In this paper, we propose a method for evaluating degradation of satellite power supply components based on clustering. We extract the degradation characteristic parameters of relevant power supply components in the telemetry data through the periodic recognition algorithm, and obtain the same power generation condition points by clustering according to the influencing factors. According to the actual power generation situation of power supply components, such as solar cell array, which is subject to the periodic influence of solar illumination and satellite orbit, the periodic formula of degradation characteristic parameters changing with time is fitted to obtain the periodic compensation. The periodic compensation is used to make up for the problem that clustering cannot completely guarantee the same power generation condition, and the steady and obvious attenuation trend is obtained. Finally, the single-year attenuation of the satellite is estimated to be 0.433 %, which conforms to the engineering design. Therefore, in this paper, based on the clustering of the satellite power component approach to estimate the degradation of short duration data has good treatment effect, providing assistance for analyzing the operation of solar cell array and battery in the early stage of satellite operation. The conclusion of this paper is valuable for the design and prediction of the power system of the geostationary orbit satellite.

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