Output Power Prediction Method of GEO Satellite Solar Array Based-on the Modified Equivalent Circuit Model

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***Abstract*—It proposed a single-exponential equivalent circuit model in order to predict the output power of geostationary satellite solar array. The key factors of the model are the short-circuit current (I_{sc}) , the open-circuit voltage(V_{oc}) , the maximum power point current (I_m) and the maximum power point voltage(V_m), which are used with corresponding coefficient to calculate the updated four parameters and *I-V* characteristics equation based on the new light intensity and temperature. Then, the power of various light intensity and temperature are calculated according to the provided voltage data, and a modified model is achieved by considering the attenuation factor. At last, this paper presents two experiments of the short-term and long-term solar array output power prediction. The comparison results of the predicted power and real power illustrate the prediction accuracy of 85%. Therefore, this power prediction model is sufficient for most engineering applications.**

***Index Terms*—solar array; equivalent circuit model; attenuation factor; power prediction**

I. Introduction

Solar array is the important energy source of the geostationary satellite; it provides electric power for the geostationary satellite during the light period, and recharges the auxiliary battery. The prediction of the output power can not only monitor its working condition, but also diagnose its future working trend and the possibility of fault. What's more, it can predict the attenuation and degradation of geostationary satellite solar array in early stage, which is of great significance to the extension of its on-orbit working life [1].

Factors that affect the power of satellite solar array can be roughly described in the following aspects. The first is the working temperature. The second is the shadow area [2]. The solar array is open circuit when not affected by light (that is, the high impedance state). For a group of tandem solar array, if a solar array slices is in the shadow, the whole bunch of solar array will have no output. The third is the loss of the particle radiation which can severely reduce the output voltage and current of the solar array. It also can degrade the performance of the solar array quickly, thus affecting the loss of the output power. The fourth is the light intensity. The increase of light intensity will lead to the increasing trend of output power of the solar array. The fifth is the performance attenuation phenomenon of the solar array [3]. In short, the output power of satellite solar array is strongly affected by the change of light intensity and temperature, comprehensive performance attenuation phenomenon is also an important factor which should be taken into account.

There are some studies on the prediction of the output power losses of GEO satellite solar array. The prediction methods about the attenuation of solar array output power can be divided into two categories, which are driven by data and based on the model. Among them, data-driven prediction methods, such as the Autoregressive Moving Average model (ARIMA), neural network, and other methods of pattern recognition have been proved applicative to both diagnostics and prognostics in many fields [4-7], but those methods make it hard to establish a general empirical model about solar array output power varying with time. The main task of prediction methods based on model are to analyze the influencing factors of solar array output power attenuation and their effect on power, and further to establish an empirical model about

doi:10.4304/jcp.9.10.2481-2487

solar array output power varying with time through a lot of simulation and historical measurement data. Then according to data from a specific system and using curve fitting to estimate the parameters of the empirical model, the concrete formula of solar array output power varying with time can be obtained, by which the output power at any time point can be achieved [8, 9]. Besides, there is also a dynamic prediction method based on model and data. In reference [10], based on the empirical equivalent circuit model, a particle filtering algorithm is formulated to predict the output power of solar arrays and update the model parameters simultaneously. Among them, the prediction method based on model is very important.

The main work of this article is the establishment of the simplified and modified equivalent circuit model for the prediction of solar array output power, which is suitable for the engineering application. The proposed modified model takes into account the attenuation factor, temperature, light intensity and other factors related to the working condition of the GEO satellite, and can be used to the short-term and long-term effective prediction of the GEO satellite solar array output power.

II. The Establishment Of Geo Satellite Solar Cell Prediction Model

According to the theory of the electronics [11], the equivalent circuit of the satellite solar cell [12] is shown in Figure 1.

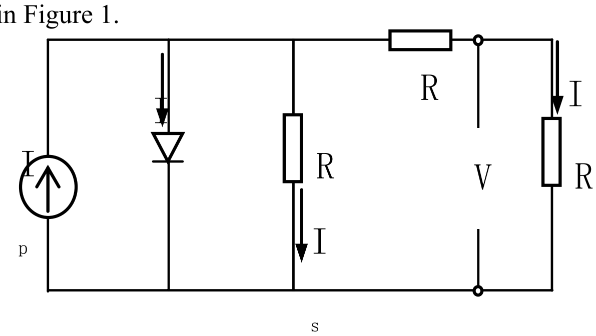

Figure1. The equivalent circuit of the solar cell.

Based on the above circuit, we can acquire the solar cell *I-V* characteristic equation for the mathematical model:

$$I = I_{ph} - I_d - I_{sh} = I_{ph} - I_0[\exp(\frac{q(V+IR_s)}{AKT}) - 1] - \frac{V+IR_s}{R_{sh}} \quad (1)$$

Where, I - the load current; I_{ph} - the light current; I_D - the diode forward current; I_{sh} - the bypass current, the current is far smaller than photocurrent and can be ignored; I_0 - the diode reverse saturation current; q -the electron charge ($1.6*10^{19}$C); V - the load voltage; R_s - the series resistance; R_{sh} - the parallel resistance; A - the diode quality factor, K - the Boltzmann constant$\left(1.38\times10^{-23} J/K\right)$; T - the absolute temperature.

Formula (1) is the basic expression based on the theory of electronics, and it is widely used in theoretical analysis of solar cell. The five parameters: I_{ph}, I_0, R_s, R_{sh} and A, are not only related to the temperature and light intensity, but also hard to confirm, so it is not convenient for engineering application[13]. The model used in engineering emphasizes the combination of practicality and accuracy, so we must simplify the model under the limitation precision of engineering [14]. The solar cell model for engineering usually can only use the several important technical parameters provided by the application user, such as I_{sc}, V_{oc}, I_m, V_m, P_m, which can describe the current and voltage characteristic of solar array under certain precision, and can be used for computer analysis.

Based on the basic analysis formula (1), we conduct the following approximation, namely: ① Ignore item $(V_L + I_L R_s)/R_{sh}$, because the item is far smaller than the photocurrent under normal circumstances. ②Set $I_{ph} = I_{sc}$, because R_s is far smaller than the diode forward connectivity resistance under normal circumstances, and on the basis of the equivalent circuit in Figure 1, and defined in open circuit state, $I = 0$, $V = V_{oc}$; under the condition of maximum power point and the condition of $V = V_m$, $I = I_m$, we can establish the engineering model of the solar cell. Thus, the solar cell *I-V* characteristic equation can be simplified as the following:

$$I = I_{sc}\{1 - C_1 \times [\exp(\frac{v}{c_2 v_{oc}}) - 1]\} \quad (2)$$

In the maximum power point, $V = V_m$, $I = I_m$, we can get $I_m = I_{sc}\{1 - C_1 \times [\exp(\frac{v_m}{c_2 v_{oc}}) - 1]\}$.

Due to $\exp(\frac{v_m}{c_2 v_{oc}}) >> 1$, we ignore the item "-1" to work out C_1:

$$C_1 = (1 - \frac{I_m}{I_{sc}}) \times \exp(-\frac{v_m}{c_2 v_{oc}}) \quad (3)$$

Under the state of open circuit, when I = 0, $V = V_{oc}$, formula (3) can be put into (2), and we can get

$$0 = I_{sc}\{1 - (1 - \frac{I_m}{I_{sc}}) \times \exp(\frac{-v_m}{c_2 v_{oc}})[\exp(\frac{1}{c_2} - 1)]\}$$

Due to $\exp(\frac{1}{c_2}) >> 1$, we ignore the item “-1” and work out the *C2:*

$$C_2 = \frac{(\frac{v_m}{v_{oc}} - 1)}{\ln(1 - \frac{I_m}{I_{sc}})} \quad (4)$$

Therefore, in this model we just need to input the technical parameters of solar cell I_{sc}, V_{oc}, I_m, V_m, then we can figure out *C1* and *C2* according to the formula (3) and (4). At last, the *I-V* characteristic equation of the solar cell is determined by formula (2).

We can figure out the *I-V* characteristic equation under different light intensity and temperature by equation (2), as the light intensity and temperature change over time, so the *I-V* characteristic equation is different over time, as shown in Figure 2.

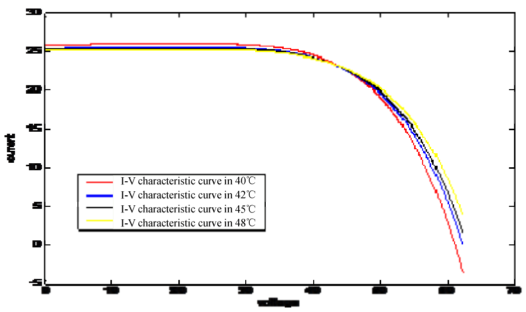

Figure 2. *I-V* characteristic curve of different temperature.

The Figure 2 shows that if we know voltage *V* in *I-V* characteristic equation, we can calculate the current *I* at this moment. Then we can build the output power model of solar cell array as follows

$$P = V \times I \times F \quad (5)$$

Where, *F* – the comprehensive attenuation factor which is used to correct the output power model and it will be elaborated in the fourth part. Take 41v for *V*, this is because most of the solar array works in voltage up and down around 41v, only a small amount of data is serious deviation under 41v. Set the data 41v for voltage, and put it into the *I-V* characteristic equation to calculate the current value quickly. It has simplified the calculation, the approximate value is allowed in engineering application, and then according to the equation (5), we can calculate the output power of solar array under different light intensity and temperature.

III. Evaluate The Parameters Of Model

The *I-V* characteristic equation of solar cell is related to the light intensity and battery temperature. By the literature [15] we can get the values of I_{sc}, V_{oc}, I_m, V_m referring to the light intensity and the cell temperature, the corresponding new light intensity and new battery temperature are I'_{sc}, V'_{oc}, I'_m, V'_m

$$\begin{cases} I'_{sc} = I_{sc} \times \frac{s}{s_{ref}}(1 + a\Delta T) \\ V'_{oc} = V_{oc}(1 - c\Delta T)(1 + b\Delta S) \\ I'_m = I_m \times \frac{s}{s_{ref}}(1 + a\Delta T) \\ V'_m = V_m(1 - c\Delta T)(1 + b\Delta S) \end{cases} \quad (6)$$

$$\begin{cases} \Delta T = T - T_{ref} \\ \Delta S = \frac{s}{s_{ref}} - 1 \end{cases} \quad (7)$$

Where, the typical value of the coefficient *a, b, c* are $a = 0.0025/°C$, $b = 0.5/°C$, $c = 0.00288/°C$, and the parameters $V_{oc} = 62.1V$; $I_{sc} = 25.7A$; $I_m = 24.25A$; $V_m = 49.3V$; $Tref = 41°C$ are provided by the application users.

Putting equations (6) and (7) into the expression (2)~(4), *I-V* characteristic equation [14]of the new light intensity and battery temperature is obtained .

IV. Correction of the Attenuation Factor

Because the performance of solar array will attenuate, we set the factor *F* as the comprehensive attenuation factor of output power of the solar array, which is caused by the change of light intensity and temperature. The *F* is used to adjust the output power model (5). To get the attenuation factor, we adopt the method of the least squares fitting and got the composite attenuation factor of the 1st year to the 8th year. It is shown in the following table.

TABLE I.
Fitting The Composite Attenuation Factor Of Each Year

Year	**Y1**	**Y2**	**Y3**	**Y4**	**Y5**	**Y6**	**Y7**	**Y8**
Attenuation factor	1.000	1.000	1.000	0.979	0.980	0.953	0.861	0.842
The sum of Error's square	1.647×10^6	1.617×10^6	1.6175×10^6	5.3546×10^6	2.5240×10^6	5.4767×10^6	4.0168×10^6	1.6192×10^6

Conducting the interpolation calculation in the attenuation factor of the 1st year to the 8th year, it is concluded that attenuation factor change rule can be shown in the figure below.

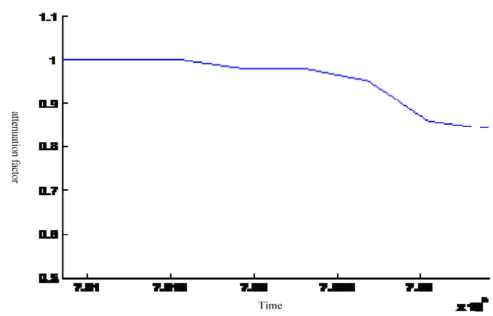

Figure 3. The change rule of attenuation factor.

V. Analyze the Prediction Results Compared with Actual Results

According to the above content, the principle of corresponding work can use the following flow chart to illustrate.

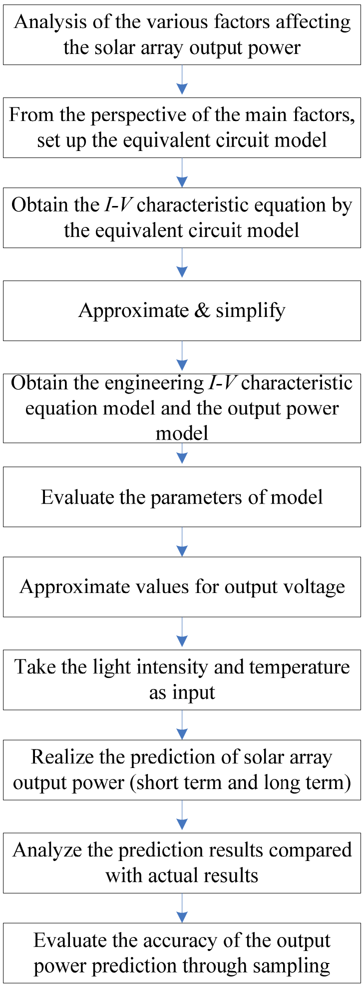

Figure 4. he flow chart of the output power prediction method of GEO satellite solar array based-on the modified equivalent circuit model.

A. Experiments of the Long- term Solar Array Output Power Prediction

According to the actual long term satellite telemetry data, we make the experiments of the 8 years' data. We can draw the graphs of actual light intensity, temperature, current and output power over time as shown in Figure 5-Figure 8.

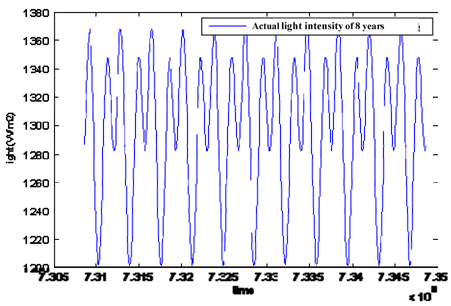

Figure 5. Actual light intensity of 8 years.

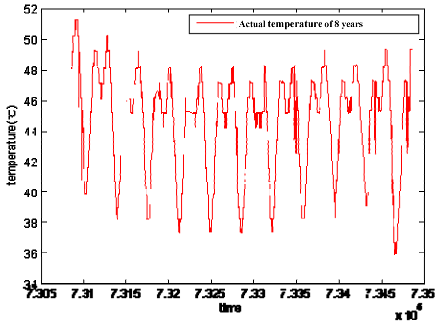

Figure 6. Actual current of 8 years.

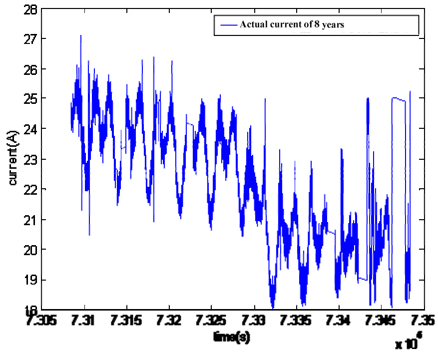

Figure 7. Actual light intensity of 8 years.

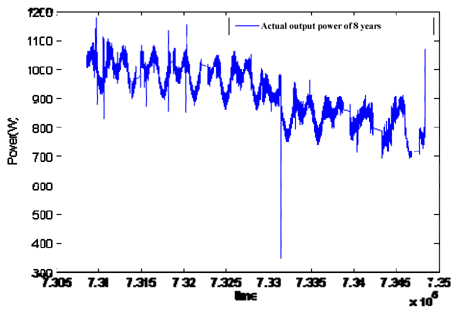

Figure 8. Actual output power of 8 years.

We adopt the output power prediction model (5) to draw the actual and forecasted *p*-*t* contrast figure of the solar array, as shown in Figure 9.

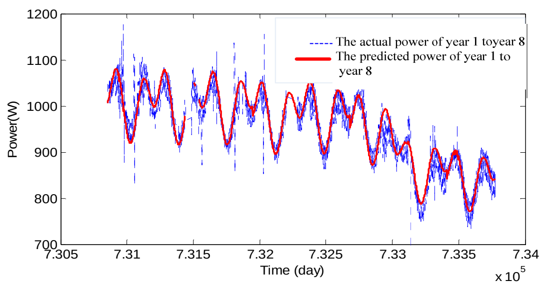

Figure 9. The measured power and predicted power contrast figure from the 1st year to the 8th year.

Set light intensity and temperature as the input of the model in the figure, and then put it into formula (7), (2) and (5). So we can predict the *p*-*t* figure of theories, and compares it with the change rule of the actual power figure. The figure also has taken into account the cause of composite attenuation factor *F* of the output power of solar array. Because of the closer of the predicted power value and the measured power value, the smaller the absolute value of the difference, the more argument to prove the accuracy of the power prediction. So the definition of prediction accuracy of the satellite solar cell power can be shown below:

$$\Pr e_{\_p} = 1 - \frac{|P_{actual} - P_{predict}|}{P_{actual}} \times 100/\% \qquad (8)$$

Where, $\Pr e_{\_p}$ - the precision of prediction of the power, P_{actual} - the actual measured power, $P_{predict}$ - the predicted power through the model.

On the basis of the formula, we sample the actuate satellite telemetry data. Namely, we can sample a set of data every day, and draw curves of power prediction accuracy as following figures.

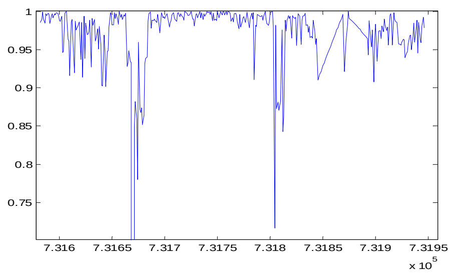

Figure 10. The change rule of power prediction accuracy in 3rd year.

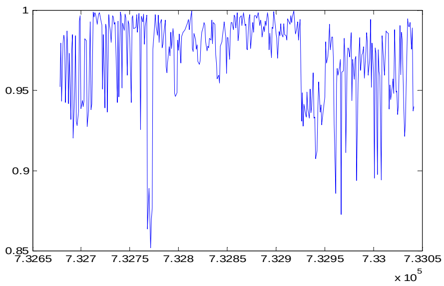

Figure 11. The change rule of power prediction accuracy in 6th year.

The sampled accuracy is checked out using the different light intensity and different temperature. The cause of errors in the project can be summed as the following [16]: ①The ignored items in the process of simplifying the formulation, such as the ignore of the item $(V_L + I_L R_s)/R_{sh}$ in formula (1). ② Set $I_{ph} = I_{sc}$, ignore the item "-1" in the formula (2). ③In the open circuit state, when $I = 0$, $V = V_{oc}$, put the formula (3) into (2), and ignore the item of "-1" to work out the $C2$. ④The influence of diode reverse saturation current, it is associated with forbidden band width of the semiconductor materials [17]. ⑤ The influence of integrity factor A, which is associated with the output voltage of satellite solar cell.

To sum up, this model can realize the power prediction of the geostationary satellite, the prediction error is generally below 15%, namely power prediction accuracy is over 85%, which can fulfill the precision requirement of engineering.

B. Experiments of the Short- term Solar Array Output Power Prediction

In view of the actual telemetry data, we make the experiments of the 5th year and the 8th year. We can draw the graphs of actual light intensity, temperature and output power over time as shown in Figure 12- Figure 17.

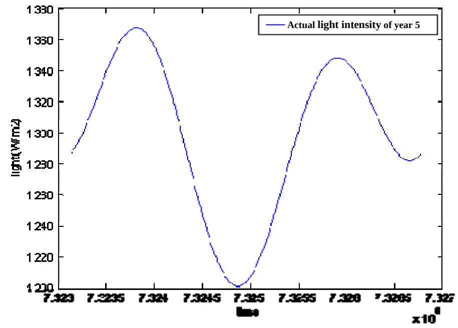

Figure 12. Actual light intensity of the 5th year.

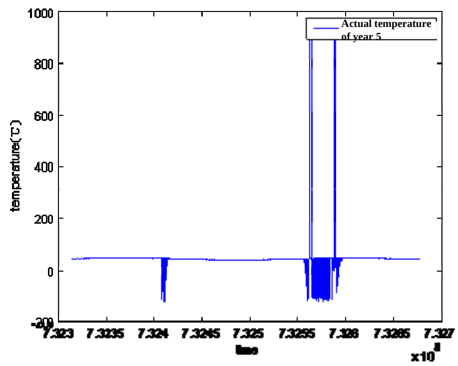

Figure 13. Actual temperature of the 5th year.

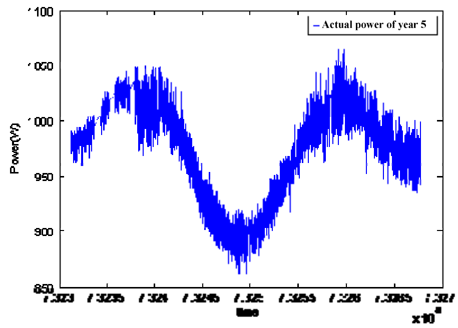

Figure 14. Actual output power of the 5th year.

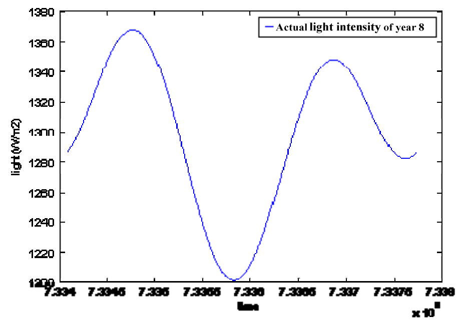

Figure 15. Actual light intensity of the 8th year.

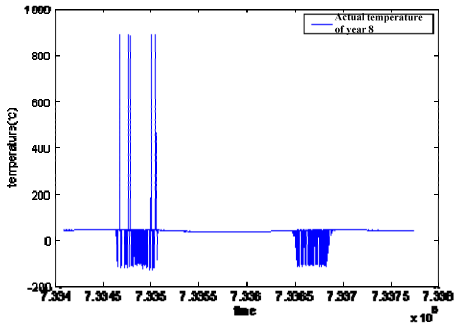

Figure 16. Actual temperature of the 8th year.

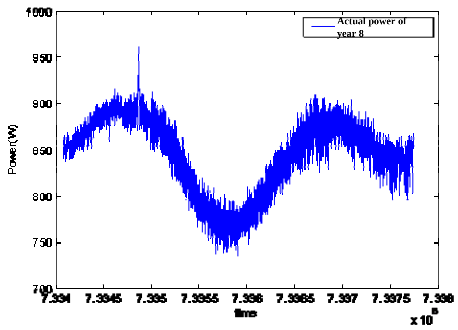

Figure 17. Actual output power of the 8th year.

The above graphs of actual light intensity and temperature can be used as the basis of input of the power prediction model. And the measured power graphs each year are important references to measure the accuracy of prediction model.

According to the proposed output power prediction model and the attenuation factor, we can draw the graphs of output power prediction results of the 5th year and the 8th year respectively, as shown in Figure 18 and Figure 19.

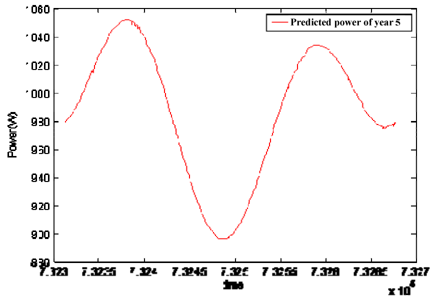

Figure 18. Output power prediction result of the 5th year.

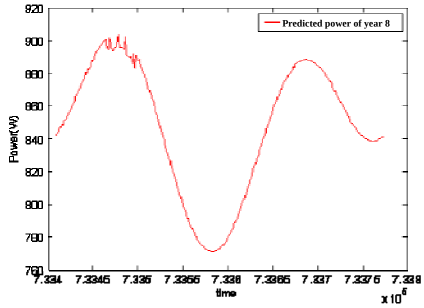

Figure 19. Output power prediction result of the 8th year.

As can be seen, the basic shape of output power prediction is similar, but it appears the attenuation phenomenon. As shown in Figure 20 and Figure 21, it analyzed the prediction result compared with actual result in the 5th year and the 8th year.

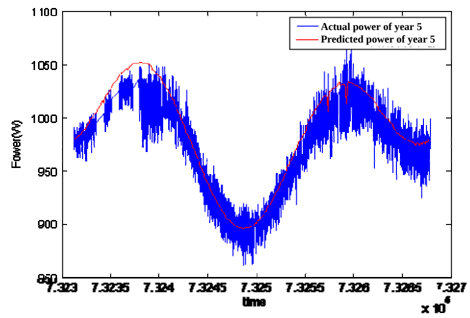

Figure 20. The prediction result compared with actual result in the 5th year.

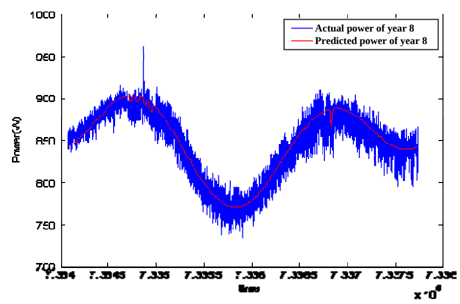

Figure 21. The prediction result compared with actual result in the 8th year.

Through the comparison and analysis, we found the accuracy of the output prediction power prediction accuracy is over 85%, which can fulfill the precision requirement of engineering, too.

VI. CONCLUSION

This paper proposes the output power prediction method of GEO satellite solar array based on the modified equivalent circuit model. It simplifies the single index equivalent circuit model of satellite solar cell, and revises the approximate model in the original project considering the comprehensive attenuation factor. It uses the model to predict the output power of the GEO satellite solar array, and compares the prediction value and the actual power. The results shows that the power predicting precision is over 85%, which can fulfill the precision requirement of engineering, and the error analysis is presented. It should be noted that the modified model does not consider the time of shadow in the calculation, because almost all shadow time appears before and after spring and autumn, and the duration time is relative less. Therefore, the model is only applicable to the rough estimation of output power. To further improve the prediction accuracy of satellite solar array power, we should start from optimizing the parameters of mathematical model and considering the calculation of shadow time.

ACKNOWLEDGMENT

This work was supported by the National Defense Basic Scientific Research program of China (Grant No. A0420110301), the National Defense Foundation of China (Grant No. 9140A17050612HT0601).

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