High-Linearized and Fast-Convergent $R_m I$ Look-up Table Control Method for Space Solar Array Simulator

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Abstract—Space solar array simulator (SSAS) is a key power input device for spacecraft power supply testing. SSASs are also required to simulate the steady-state I-V curve with a high tangent slope of the aerospace solar panel output and to have the dynamic response performance of the fast convergence to switching working point under a spacecraft power supply test environment. This paper proposes a high-linearized and fast-convergent $R_m I$ (HLFC- $R_m I$) look-up table control method, which is aimed at solving these problems. This study converts the conventional voltage-current UI data table into the corresponding impedance-current $R_m I$ data table without adding any auxiliary hardware circuit. The $R_m I$ data table is used as a target form for I-V outer loop control, by using the proposed equivalent impedance R_m linearization formula, thereby achieving the simulation of a high tangent slope I-V curve. In the process of looking up table control, the optimized equivalent impedance $R_{m_real-time}$ linearization formula is used to approximate the high-speed convergence characteristics of the UI look-up table method under constant-voltage load switching conditions. The new I-V outer loop control method is applied to a 1 kW hardware power platform of SSAS. The SSAS can not only simulate an arbitrary I-V curve with a high tangent slope but also has the characteristics of high-speed convergence of the switching working point.

Index Terms—Dynamic characteristics, look-up table control method, nonlinear I-V outer loop, solar array simulator, tangent slope of the I-V curve.

I. INTRODUCTION

SPACE solar array simulators (SSASs) are used to replace real solar panels in the ground test period to provide energy input to the power supply under test and play an important role in the spacecraft power test system. The closer the SSAS output characteristics are to the output characteristics of real solar panels, the more reliable the spacecraft power system can be tested. A three-junction gallium arsenide solar panel is widely used in the aerospace field because of its high-power output efficiency, which has a high tangent slope of the

output I-V characteristic curve and high dynamic response performance [1]. In general, SSASs use linear power units to improve the dynamic response performance of hardware systems, and the recently published [2] and [3] both use multi-path parallel current sources to output the power I-V curves. However, these types of SSAS still lack the simulation capability for high tangent slopes I-V curves depends on the I-V outer loop control method.

The implementation methods of existing outer loop control methods of a solar array simulator [4] are mainly divided into two categories. One category involves the use of analog hardware implementation method to complete the I-V outer loop control for the solar array simulator. They adopt an experimental PV equivalent circuit with diodes to generate the I-V reference curves, such as in [5]–[7]. Similar, [8] uses a hardware circuit to generate the corresponding five-parameter single-diode I-V reference curve output that is based on the five-parameter model of a PV panel. In applications where the dynamic response performance is not high, hardware-in-loop simulation methods can be used in PV simulators [9].

The second category includes the implementation method of a digital I-V outer loop based on a high-performance digital controller, which is the most commonly used controller in the solar array simulator products. The digital I-V outer loop control method is more flexible and can use a conjugate gradient optimization to extract PV model parameters from changing conditions and rapidly reconstruct the exact I-V curve, which is based on the single-diode model of a PV panel [10]. An exponential model of a solar cell has been converted into a polynomial model by means of polynomial fitting to facilitate real-time calculation [11]. The application of the dual diode mathematical model is simplified in [12], [13] with the aim of reducing the calculation time.

A solar array simulator device can be set different I-V curves depending on the various needs of users. An SSAS generally uses the general index model mentioned in [14] and [15] to generate the target I-V curve. It then achieves I-V outer loop control by using a digital controller. The general exponential mathematical model is shown in the following (1) – (4). Users only need to set four parameters of the I-V curve, which are open circuit voltage U_{oc} , short circuit current I_{sc} , maximum power point voltage U_{mp} , and maximum power point current I_{mp} . Furthermore, the relationship between the voltage U_{sas} and current I_{sas} at the working points of the I-V curve can be obtained.

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$$R_s = \frac{U_{oc} - U_{mp}}{I_{mp}} \quad (1)$$

$$N = \frac{\ln(2 - 2^a)}{\ln\left(\frac{I_{mp}}{I_{sc}}\right)} \quad (2)$$

$$a = \frac{U_{mp} \left(1 + \frac{R_s I_{sc}}{U_{oc}}\right) + R_s (I_{mp} - I_{sc})}{U_{oc}} \quad (3)$$

$$U_{sas} = \frac{U_{oc} \ln \left[2 - \left(\frac{I_{sas}}{I_{sc}} \right)^N \right]}{\ln(2)} - R_s (I_{sas} - I_{sc}) \quad (4)$$

$$1 + \frac{R_s I_{sc}}{U_{oc}}$$

To solve the nonlinear problem of I-V curve simulation, [16] proposes a UI-RI hybrid look-up table method, shown in Fig. 1, which overcomes the difficulty of guaranteeing stable output characteristics. But the UI-RI hybrid look-up table method cannot achieve a high accuracy simulation ability, output the open circuit voltage working point and simulate the any given data table curves capability. So, it is different to be applied to actual SSAS equipment. And the UI-RI hybrid look-up table method only has a good convergence performance for resistive loads switching condition, and it cannot have high-speed convergence characteristics for constant-voltage switching loads that the spacecraft power supply test is equivalent to constant-voltage switching loads. It can also divide the I-V characteristics curve into three segments by using different control methods in different segments to deal with the simulation problem of the high nonlinear characteristics of an I-V curve [17]. A double current mode controller is used in [18] to ensure fast and accurate reproduction of the I-V characteristics of a module. To solve the problem of control in different regions, [19] introduces a novel hysteresis controller to ensure effective operation in both these regions.

The resistance-current (RI) look-up table method is used for resistance feedback control and can be derived from the UI model [20], shown in Fig. 2(a). A similar solution is presented in [21], where the output is controlled by a voltage mode control, but the reference voltage is calculated by an impedance. A novel single controller scheme is introduced in [22] to eliminate mode transitions, where the operating point projection technique enables simple, smooth, and numerically stable control. A novel equivalent impedance-current ($R_m I$) control method, called the operating point projection $R_m I$ look-up table method, is presented in [22]. The schematic diagram of the relationship between the equivalent impedance and the I-V curve is shown in Fig. 2(b).

The equivalent impedance calculation formula proposed in [22], represented by formula (5) can be used to linearize the traditional RI model curves to obtain the equivalent $R_m I$ model curves, which can ensure smooth and numerically stable control.

Fig. 1. Schematic diagram of UI-RI hybrid look-up table method.

Fig. 2. Schematic diagram of the relationship between the equivalent impedance and the I-V curve with the traditional impedance current look-up table. (a) Traditional RI look-up table method. (b) Operating point projection $R_m I$ look-up table method.

$$R'_m = \frac{U_{sas} + U_{oc}}{I_{sas} + I_{sc}} \quad (5)$$

The HLFC- $R_m I$ look-up table method with high linearity and high-speed convergence characteristics proposed in this paper is based on the operating point projection $R_m I$ table look-up method. This makes the proposed method more suitable for application to space solar array simulator equipment in spacecraft power test condition.

II. PROPOSED HIGH-LINEARIZED AND FAST-CONVERGENT $R_m I$ LOOK-UP TABLE CONTROL METHOD

A. Proposed Hardware System Schematic

The configuration and control diagram of the proposed system is shown in Fig. 3. The system structure is based on published articles [3], where the structural design and theoretical analysis are described in detail. The innovation of the present study is based on a similar multi-level bus tracking unit in [3]

Fig. 3. Block diagram of SSAS control structure under multi-level bus tracking architecture. (a) The configuration diagram. (b) The control diagram.

with 10 levels and a similar linear current source unit in [2] with 10 parallel linear current sources. The digital I-V outer loop controller uses a similar FPGA digital hardware control platform to implement the look-up table outer loop control.

As shown in Fig. 3(a), the SSAS only needs to sample the output terminal voltage U_{sas} , and the I-V outer loop controller performs the linearization processing of the LHFC- $R_m I$ look-up table method, according to U_{sas} . The controller outputs the current control reference value, U_{Iref} , for the linear current source unit to control the SSAS output power current, I_{sas} . Simultaneously, the bus tracking outer loop controller outputs the corresponding switch control signal of the multi-level bus tracking unit based on the voltage information of the output terminal, U_{sas} , to ensure that the bus voltage U_{bus} can track changes in output terminal voltage U_{sas} in time.

The control diagram of the entire SSAS system structure can be obtained, as shown in Fig. 3(b). The mathematical model G_{Linear_10path} of the linear VCCS, from the reference voltage $U_{Iref}(s)$ to the output current $I_{lin}(s)$, is known from a previous article [2]. The model G_{PSRR_iiin} of the linear VCCS, from the drain voltage of linear power transistor $U_d(s)$ to output power current $I_{in_tot}(s)$, and the mathematical model $G_{multi-level}$ of the multi-level bus tracking converter, from $U_{sas}(s)$ to $U_{bus}(s)$, have been derived and analyzed in the previous article [3]. The HLF-C- $R_m I$ look-up table I-V outer loop control method proposed in this paper uses $U_{sas}(q)$ and $I_{sas_ref}(q-1)$, which will be introduced below, to calculate the equivalent impedance $R_{m_real-time}$ according to the proposed linearized impedance formula. Then, by looking up the HLF-C- $R_m I$ data table, the target current reference value $U_{Iref}(s)$ is obtained to control the output power current of the linear VCCS unit.

Fig. 4. Problems in the operating point projection $R_m I$ look-up table method. (a) The “hysteresis” curve problem in the steady-state I-V curve. (b) Low simulation accuracy problem of I-V curves with different tangent slopes. (c) Convergence to target working point is too slow under switching working point conditions.

B. Problems Existing in the Operating Point Projection $R_m I$ Look-up Table Method

The following three problems are associated with the operating point projection $R_m I$ look-up table method, and these are shown in Fig. 4.

1) The steady-state I-V output curve of the projection $R_m I$ look-up table at the working point will exhibit a significant “hysteresis” curve problem near the operating point of the open circuit voltage, as shown in Fig. 4(a). Fig. 4(a) shows the experimental waveform

of the steady-state I-V curve obtained using the operating point projection R_m I look-up table method on the hardware platform shown Fig. 4. The parameters of the I-V curve are set as follows: U_{oc} is 35 V, I_{sc} is 10 A, U_{mp} is 32 V, and I_{mp} is 9.5 A. The maximum tangent slope $(dI/dU)_{max}$ is 3.45 A/V. The SSAS output is connected to a constant-voltage electronic load. The load is slowly switched from 0 V to 35 V at a frequency of 5 Hz, thereby scanning all working points on the I-V curve.

2) The operating point projection R_m I look-up table method has a poor simulation accuracy of different I-V curves with different maximum tangent slopes, as shown in Fig. 4(b). Fig. 4(b) shows the maximum tangent slope of the set I-V curves by varying U_{mp} in a group and keeping the values of U_{oc} , I_{sc} , and I_{mp} the same. The values of U_{mp} corresponding to Curve 1, Curve 2, Curve 3, and Curve 4 are 28 V, 29 V, 30 V, and 32 V, respectively. The corresponding operating point projection R_m I data curves can be compared under the conditions of the four set I-V curves.

3) The convergence speed to the target operating point of the operating point projection R_m I look-up table method is low under the switching constant voltage load condition, as shown in Fig. 4(c). Fig. 4(c) shows the experimental waveform of switching between short-circuit and constant-voltage loads of 95 V at 1.25 kHz obtained using the operating point projection R_m I look-up table method with the following values of the I-V curve: U_{oc} is 100 V, I_{sc} is 10 A, U_{mp} is 90 V, and I_{mp} is 8 A. The corresponding switching working points lie between working point A (0 V, 10 A) and working point B (95 V, 4 A) on the I-V curve. This feature makes the operating point projection R_m I look-up table method unsuitable for operation under a spacecraft power supply test environment.

The HLFC- R_m I look-up table control method proposed in this paper is based on the operating point projection R_m I look-up table method. The proposed HLFC- R_m I look-up table control method can not only solve the problem of poor simulation accuracy of the I-V curve of the operating point projection R_m I look-up table method but also ensure rapid convergence to the target working point under the condition of switching working points. The characteristics of the HLFC- R_m I look-up table method make it more suitable for spacecraft power test applications.

C. Proposal of HLFC- R_m I Look-up Table Outer Loop Control Method

The projection origin coordinate of the operating point projection R_m I look-up table method is $(-U_{oc}, -I_{sc})$, and the equivalent impedance calculation formula is represented by the above formula (5).

Based on the conclusions of the above analysis, the linearization formula for the HLFC- R_m I look-up table method is derived as follows:

$$R_m = \frac{U_{sas}}{I_{sas} + k \cdot I_{sc}} \quad (6)$$

Where R_m is the equivalent impedance of the HLFC- R_m I look-up table method, and k is the linearization coefficient in

the equivalent impedance calculation formula of the HLFC- R_m I look-up table method. Furthermore, the minimum equivalent impedance value R_{m_min} is 0 Ω , and the maximum equivalent impedance value R_{m_max} can be obtained as follows:

$$R_{m_max} = \frac{U_{oc}}{k \cdot I_{sc}} \quad (7)$$

The projection origin point of the HLFC- R_m I look-up table method always moves on the vertical axis $(0, -k \cdot I_{sc})$. The range of R_m is 0 – R_{m_max} and the number of data points in the HLFC- R_m I look-up table, $N_{address}$, is fixed. Therefore, there is an optimal linearization coefficient k value, which not only ensures that R_{m_max} has an optimal value but also ensure that the I_{sas} vs. R_m and U_{sas} vs. R_m curves have good linearity, which is beneficial to I-V outer loop control.

The analysis process for the selection of an optimal value of the linearization coefficient k , is shown in Fig. 5. Fig. 5(a) shows a schematic diagram of I_{sas} vs. R_m , U_{sas} vs. R_m , I_{sas} vs. U_{sas} , and P_{sas} vs. R_m curves for a low value of k . Fig. 5(b) shows I_{sas} vs. R_m , U_{sas} vs. R_m , I_{sas} vs. U_{sas} , and P_{sas} vs. R_m curves for a high value of k ; Fig. 5(c) shows a schematic diagram of I_{sas} vs. R_m , U_{sas} vs. R_m , I_{sas} vs. U_{sas} , and P_{sas} vs. R_m curves for k -optimal conditions.

The following conclusions can be drawn from the analysis diagram of Fig. 5:

1) When the value of the linearization coefficient k is low, shown in Fig. 5(a), the ratio of the R_m address occupied by region B is small that having a large variation range of the voltage U_{sas} . Furthermore, the ratio of the R_m address occupied by region A is large that having a large variation range of the current I_{sas} . The linearity of voltage control is poor, which would lead to “hysteresis” within the open circuit voltage region of the I-V curve. From the perspective of the SSAS output power P_{sas} in the region A, the linearity of the output power control is good, but the linearity of the output power P_{sas} in the region B is poor. The output power P_{sas} is difficult to maintain stable power controlling in the full range of R_m .

2) When the value of the linearization coefficient k is high, shown in Fig. 5(b), the ratio of the R_m address occupied by region B is large that having a large variation range of the voltage U_{sas} . And the ratio of the R_m address occupied by region A is small that having a large variation range of the current I_{sas} . The linearity of current control is poor, which could lead to current oscillation problem under steady-state working conditions. The SSAS output power P_{sas} in the region B, the linearity of the output power control is good, but the linearity of the output power P_{sas} in the region A is poor. The output power P_{sas} is difficult to maintain stable power controlling in the full range of R_m , either.

3) When both region A and region B corresponding to I_{sas} and U_{sas} have a half address ratio of $1/2 R_{m_max}$, shown in Fig. 5(c), it can simultaneously ensure that voltage U_{sas} and current I_{sas} both have a better control linearity for R_m . That is, the intersection of the I_{sas} vs. R_m curve and U_{sas} vs. R_m curve, the equivalent impedance value R_{m_mp} corresponding to the maximum power point (U_{mp}, I_{mp}) , is $1/2 R_{m_max}$, and the obtained value of k value is

Fig. 5. The HLFC- R_m I look-up table method corresponds to I_{sas} vs. R_m , U_{sas} vs. R_m , and I_{sas} vs. U_{sas} curves under different linearization coefficients k . (a) The linearization coefficient k is small. (b) The linearization coefficient k is large. (c) The linearization coefficient k is the optimal value.

optimal. At the same time, it also ensures that the output power P_{sas} has good linearity in both region A and region B, and has stable power controlling in the full range of R_m .

Substituting the open circuit voltage operating point (U_{oc} , 0) and the maximum power operating point (U_{mp} , I_{mp}) in (6), the maximum equivalent impedance R_{m_max} and the equivalent impedance R_{m_mp} at the maximum power operating point can be obtained as follows:

$$R_{m_max} = \frac{U_{oc}}{k \cdot I_{sc}} \quad (8)$$

$$R_{m_mp} = \frac{U_{mp}}{I_{mp} + k \cdot I_{sc}} \quad (9)$$

Based on the above condition that the linearization coefficient k has an optimal solution, we have

$$R_{m_mp} = \frac{1}{2} R_{m_max} \quad (10)$$

Substituting (8) and (9) into (10), we have

$$\frac{U_{mp}}{I_{mp} + k \cdot I_{sc}} = \frac{1}{2} \cdot \frac{U_{oc}}{k \cdot I_{sc}} \quad (11)$$

The parameter expression of the optimal linearization coefficient k can be solved as follows:

$$k = \frac{U_{oc}}{2U_{mp} - U_{oc}} \cdot \frac{I_{mp}}{I_{sc}} \bigg|_{U_{mp} > \frac{1}{2} U_{oc}} \quad (12)$$

According to the parameter expression of the optimal linearization coefficient k , there is a corresponding optimal R_{m_max} value for each specific I-V curve set, and I_{sas} vs. R_m and U_{sas} vs. R_m curves with higher linearity. However, the parameter expression of the optimal linearization coefficient k requires that the maximum power point voltage should not be less than half the open circuit voltage. Furthermore, under normal application, the maximum power point voltage will not be less than half the open circuit voltage.

D. Derivation of Exponential Model for Generating the Table of HLFC- R_m I Look-up Table Method

It is known that the origin projection coordinates of the HLFC- R_m I look-up table method is (0 V, $-k \cdot I_{sc}$). Thus, the relationship between the equivalent output terminal voltage and current, U'_{sas} and I'_{sas} , and that between the actual output terminal voltage and current, U_{sas} and I_{sas} , are given by the following (13) and (14):

$$U'_{sas} = U_{sas} \quad (13)$$

$$I'_{sas} = I_{sas} + k \cdot I_{sc} \quad (14)$$

U_{sas} and I_{sas} can be simplified using the formula, and (15):

$$U'_{sas} = \frac{U_{oc} \ln \left[2 - \left(\frac{I'_{sas}}{I_{sc}} - k \right)^N \right]}{\ln(2)} - R_s \left[I'_{sas} - (1 + k) I_{sc} \right] \quad (15)$$

$$1 + \frac{R_s I_{sc}}{U_{oc}}$$

Finally, the equivalent impedance R_m of the HLFC- R_m I look-up table method is formula (16):

$$R_m = \frac{U'_{sas}}{I'_{sas}} = \frac{U_{oc} \ln \left[2 - \left(\frac{I'_{sas}}{I_{sc}} - k \right)^N \right]}{I'_{sas} \times \ln(2)} - R_s \left[1 - \frac{(k + 1) I_{sc}}{I'_{sas}} \right] \quad (16)$$

$$1 + \frac{R_s I_{sc}}{U_{oc}}$$

The index model corresponding to the equivalent $R_m I$ table is obtained using (1) to (3) and (16). The data table corresponding to I_{sas} vs. R_m can be calculated through dichotomous rooting under the condition of equal spacing R_m . It is then calculated according to formula (14) to obtain the target current-impedance data table, I_{sas} vs. R_m .

The look-up data table curves generated by the HLFC- $R_m I$ look-up table method is determined by U_{oc} , I_{sc} , U_{mp} , and I_{mp} . Thus, theoretically, it will have a higher curve simulation accuracy. A comparison of the look-up data table curves generated by the different look-up table methods are shown in Fig. 6. The maximum tangent slopes of the set I-V curves are changed by varying U_{mp} in a group with the same U_{oc} of 35 V, I_{sc} of 10 A, I_{mp} of 9.5 A, and different values of U_{mp} .

It can be seen from Fig. 6 that the operating point projection $R_m I$ look-up table method has almost the same target data tables under the condition of I-V curves with different tangent slopes, so it is difficult to have good simulation accuracy of the I-V curve. The UI target data tables have a relatively good resolution of different curves with different tangent slopes. However, the UI data tables cannot simulate the I-V curve with a high tangent slope because the target table has severe nonlinear characteristics. For the $R_m I$ data tables of the HLFC- $R_m I$ look-up table method, by selecting the optimal linearization coefficient k , the poor simulation accuracy of the I-V curves and the “hysteresis” curve in the constant voltage region of the operating point projection $R_m I$ look-up table method can be solved.

E. Design of Fast Convergent Characteristics of HLFC- $R_m I$ Table Look-up Method

Another advantage of the HLFC- $R_m I$ look-up table method compared with the operating point projection $R_m I$ look-up table method is its fast convergence characteristic under the condition of switching working points. As the operating point projection $R_m I$ table look-up method, the digital I-V outer loop controller samples the output voltage U_{sas} and current I_{sas} in real-time and calculates the equivalent impedance of the current look-up table period for looking up the $R_m I$ data table. Combined with the optimal linearization coefficient proposed in the previous section, the formula for calculating the real-time equivalent impedance R_{m_pre} of the optimized operating point projection $R_m I$ look-up table method is given as follows:

$$R_{m_pre}(q) = \frac{U_{sas}(q)}{I_{sas}(q) + k \cdot I_{sc}} \quad (17)$$

where q is the current look-up table period of the digital I-V outer loop, $U_{sas}(q)$ is the sampled voltage value during the current q look-up table period, $I_{sas}(q)$ is the sampled current value during the current q look-up table period, and $R_{m_pre}(q)$ is the equivalent impedance during the current q look-up table period calculated by the operating point projection $R_m I$ look-up table method with the optimal linearization coefficient k .

Under the condition of equivalent impedance, the specific

Fig. 6. Comparison of the target look-up table curves with different look-up table methods. (a) Comparison of the operating point projection $R_m I$ table curves. (b) Comparison of the UI table curves. (c) Comparison of the proposed HLFC- $R_m I$ table curves.

process of convergence to the target working point during the switching process of the operating point can be derived, and the speed of convergence to the target working point can be derived. The operating point projection $R_m I$ look-up table method is switched from the short-circuit working point A (0 V, I_{sc}) to the rated working point B (U_B , I_B) under the constant-voltage load switching condition and the convergence process is shown in Fig. 7(a).

The convergence process and speed of constant-resistance load switching and constant-voltage load switching are inconsistent, while the switching of the operating points of the spacecraft power supply testing are similar to constant-voltage loads switching. The constant-voltage load is instantaneously switched from CV_A is 0 V to the CV_B is U_B . In the first cycle of the look-up table, the output current $I_{sas}(1)$ keeps the short-circuit current I_{sc} unchanged, reaches the intermediate temporary working point I_1 , and the digital controller calculates the effective impedance $R_{m_pre}(1)$, as follows:

Fig. 7. Schematic diagram of convergence process with different outer loop control methods under constant voltage load working point switching conditions. (a) The operating point projection $R_m I$ look-up table method. (b) The proposed HLFC- $R_m I$ look-up method. (c) The traditional UI look-up method.

$$R_{m_pre}(1) = \frac{U_B}{I_{sc} + k \cdot I_{sc}} \bigg|_{I_{sas}(1) = I_{sc}} \quad (18)$$

The $R_m I$ look-up table data provide the control current value corresponding to the working point $P_1 (U_{P_1}, I_{P_1})$ on the set I-V curve. However, owing to the limitation of the dynamic response performance of the power in the hardware system, the current corresponding to the P_1 working point cannot be established instantaneously. However, the power current value of the working point $P_{1_pre} (U_{P_{1_pre}}, I_{P_{1_pre}})$ is reached, that is,

$$I_{sas}(2) = I_{P_{1_pre}} \big|_{I_{P_{1_pre}} > I_p} \quad (19)$$

The steady-state working condition is not achieved; thus, the digital controller initiates the second look-up table cycle.

According to the current output terminal voltage U_B and the current value $I_{sas}(2)$, represented by (19), reaches the second intermediate temporary working point I_2 , and the second equivalent impedance $R_{m_pre}(2)$ is calculated as follows:

$$R_{m_pre}(2) = \frac{U_B}{I_{P_{1_pre}} + k \cdot I_{sc}} \bigg|_{I_{sas}(2) = I_{P_{1_pre}}} \quad (20)$$

The target current of working point $P_2 (U_{P_2}, I_{P_2})$ is sent out, and the $P_{2_pre} (U_{P_{2_pre}}, I_{P_{2_pre}})$ working point of current $I_{P_{2_pre}}$ is established.

By analogy, the convergence process of the optimal operating point projection $R_m I$ look-up table method at a constant-voltage load needs to gradually converge to the target operating point and the approximate number of lookup cycles required is n . Because of the settling speed of the current in the hardware power current is slow relative to that of the digital controller look-up speed, the speed of convergence to the target operating point decreases further.

The proposed HLFC- $R_m I$ look-up table method improves the calculation formula of real-time equivalent resistance. The formula for calculating the real equivalent impedance is given as follows:

$$R_{m_real-time}(q) = \frac{U_{sas}(q)}{I_{sas_ref}(q-1) + k \cdot I_{sc}} \quad (21)$$

When $(q-1)$ is the previous look-up table cycle, the control command current value transmitted by the digital I-V outer loop controller to the linear hardware current source is I_{sas_ref} . The proposed HLFC- $R_m I$ look-up table method calculates the value of current of the equivalent resistance $R_{m_real-time}$ in the real-time lookup table process by using the control target current value transmitted from the previous lookup table cycle. The convergence process is shown in Fig. 7(b).

Because only the real-time sampling output voltage U_{sas} is needed for calculating the equivalent impedance, the current value of the output terminal need not be sampled in real time. In the first cycle of the look-up table, the current control reference value $I_{sas}(0)$ is the short-circuit current I_{sc} , and the effective impedance $R_m(1)$ is calculated by the digital controller as follows:

$$R_m(1) = \frac{U_B}{I_{sc} + k \cdot I_{sc}} \bigg|_{I_{sas}(0) = I_{sc}} \quad (22)$$

The HLFC- $R_m I$ look-up table data provide the control current value corresponding to the working point $P_1 (U_{P_1}, I_{P_1})$ on the set I-V curve. Then, the second look-up table cycle is initiated, and the equivalent impedance, $R_m(2)$, is calculated:

$$R_m(2) = \frac{U_B}{I_{P_1} + k \cdot I_{sc}} \bigg|_{I_{sas}(1) = I_{P_1}} \quad (23)$$

Thus, the entire convergence process of switching operating

Fig. 8. Photo of the prototype.

point only requires a dozen look-up table periods, q , for the digital controller calculation and the expected current value corresponding to the final target working point can be achieved. The process of convergence under the constant-voltage load switching condition is a theoretical $R_m I$ table convergence process. Comparing (a) and (b) of Fig. 7, the number of look-up table cycles, n , required for convergence to the target working point is much larger than the number of look-up table cycles of q from Fig. 7(b).

Because the spacecraft power test field is similar to the switching of the constant-voltage load working point, the theoretical convergence rate is determined using the UI look-up table method. The switching convergence process is shown in Fig. 7(c). When the working point is switched from the short-circuit working point A (0 V , I_{sc}) to the rated working point B (U_B , I_B), according to the UI look-up table working logic, the target current value I_B corresponding to the working point B is directly outputted and remains unchanged. The SSAS target working point current establishing process is the hardware current steady state establishing process.

Although the speed at which the HLFC- $R_m I$ look-up table converges to the target working point is lower than that of the UI look-up table, the time relative to the settling time of the hardware power current established is almost negligible because the look-up cycle time is nanosecond. Therefore, theoretically, the convergence speed of the HLFC- $R_m I$ and UI look-up table methods is similar under the constant-voltage load switching condition.

III. EXPERIMENTAL RESULTS AND DISCUSSIONS

The superior performance of the HLFC- $R_m I$ look-up table method is verified from two aspects. One is the steady-state response along a static I-V curve, which aims to demonstrate that the HLFC- $R_m I$ look-up table method has excellent curve simulation accuracy and can simulate any high tangent slope I-V curves. The other is the high-speed convergence to the target working point of the HLFC- $R_m I$ look-up table method under constant-voltage load working point switching conditions. A photograph of the prototype, which is a 1-kW hardware power platform of SSAS, is shown in Fig. 8.

Fig. 9. Comparison of steady-state I-V curves of two look-up table methods to verify whether the HLFC- $R_m I$ look-up table method solves the “hysteresis” curve problem. (a) The proposed HLFC- $R_m I$ lookup table method. (b) The operating point projection $R_m I$ look-up table method.

A. Steady-State I-V Curves Output Test Experiment

To verify whether the HLFC- $R_m I$ look-up table method solves the “hysteresis” curve problem in the constant-voltage region of the I-V curve by the operating point projection $R_m I$ look-up table method, the experimental verification waveforms are shown in Fig. 9 that shows a comparison of the steady-state I-V output curves for the two look-up table control methods. The test condition of the steady-state I-V curve is: the SSAS output terminal is connected to the electronic load with constant voltage mode, and the set scanning voltage value is from 0.1 V to 35 V at 5 Hz . At the same time, using an oscilloscope to record the output voltage U_{sas} , output current I_{sas} and the multi-level tracking bus voltage U_{bus} .

Fig. 9(a) show the simulation I-V curves obtained using the HLFC- $R_m I$ look-up table method, and (b) shows the simulated I-V curves using the operating point projection $R_m I$ look-up table method. In the figure, U_{bus} is the bus voltage waveform output by the multi-level bus tracking unit, and U_{sas} and I_{sas} denote the voltage and current waveforms of the SSAS output, respectively.

Fig. 10. Comparison of output steady-state full power I-V curves with the HLFC- $R_m I$ look-up table method and UI look-up table method for different tangent slopes. (a) The proposed HLFC- $R_m I$ look-up table method. (b) The UI look-up table method.

It can be seen from Fig. 9 that the HLFC- $R_m I$ look-up table method solves the problem of “hysteresis” curve in the constant-pressure region of the I-V curve because of the operating point projection $R_m I$ look-up table method and can also stably simulate different I-V curve with different maximum tangent slopes.

Simultaneously, it is necessary to compare the steady-state simulation of the I-V curves with the HLFC- $R_m I$ and UI look-up table methods. Therefore, a full power I-V curves are set that the parameters of the curve with ultra-high maximum tangent slope are as follows: U_{oc} is 100 V, I_{sc} is 10 A, U_{mp} is 99 V, I_{mp} is 9 A, and the maximum tangent slope $(dI/dU)_{max}$ is 9.1 A/V. The corresponding steady-state I-V curves obtained by the experiment is shown in Fig. 10. Fig. 10(a) is the steady-state experimental waveforms obtained by the HLFC- $R_m I$ look-up table method, and Fig. 10(b) show the steady-state experimental waveforms obtained by the UI look-up table method.

Fig. 10 shows that, for an I-V curve with a high tangent slope, the UI look-up table method cannot stably simulate the I-V curve, and oscillation occurs at the working points where

the tangent slopes are too large, while the HLFC- $R_m I$ look-up table method can still stably output an I-V curve with a high tangent slope.

The experimental results prove that the proposed HLFC- $R_m I$ look-up table method can simulate the I-V curves with any high tangent slopes. This means that the SSAS with the HLFC- $R_m I$ look-up table method can simulate the output I-V curves of the solar panel with the three-junction gallium arsenide that are usually used in the aerospace field to reliably test the spacecraft power system.

B. Shunt Switching Convergence Speed Test Experiment

To verify whether the proposed HLFC- $R_m I$ look-up table method solves the problem that the operating point projection $R_m I$ look-up table method converges to the target working point too slowly, and its convergence speed is almost equal to that of the UI look-up table method. The setting curve has U_{oc} of 100 V, I_{sc} of 10 A, U_{mp} of 90 V, I_{mp} of 8 A, the SSAS output is switched between the short-circuit working point A (0 V, 10 A) and the rated working point B (95 V, 4 A) in the form of a constant voltage load, and the switching frequency is 1.25 kHz. The comparison of the switching experiment waveforms obtained using the HLFC- $R_m I$ look-up table method, operating point projection $R_m I$ look-up table method, and UI look-up table method are shown in Fig. 11.

From Fig. 11, it can be seen that the HLFC- $R_m I$ look-up table method can quickly converges to the target working point. In addition, during the switching process from the working point A to the working point B, the convergence time of the HLFC- $R_m I$ look-up table method is 64 μs , the operating point projection $R_m I$ look-up table method cannot establish a stable target working point, and the UI look-up table method, which has the ideal convergence speed, requires a convergence time of 60 μs . During the switching process from the working point B to the working point A, the convergence time of the HLFC- $R_m I$ look-up table method is 19 μs , the operating point projection $R_m I$ look-up table method requires 22 μs , and the UI look-up table method, which has the ideal convergence speed, requires the convergence time of 16 μs . It should be noted that in Fig. 11, t_{A2B} is the respond time that I_{sas} is first reaching within the range of $(0.9 - 1.1) I_B$ when switching from operating point A to operating point B. Similarly, t_{B2A} refers to the time within the range of the first reaching $(0.9 - 1.1) I_A$.

The second shunt switching test experiment is switched between the short circuit working point A (0 V, 10 A) and the open circuit working point C (100 V, 0 A), which is the harshest working condition for SSAS. The comparison of the switching experiment waveforms obtained with the HLFC- $R_m I$ look-up table method, operating point projection $R_m I$ look-up table method, and UI look-up table method are shown in Fig. 12.

From the comparison waveforms in Fig. 12, we can draw an similar experimental conclusion to Fig. 11, that is, even if under the switched between the short-circuit working point and the open-circuit working point condition, the SSAS with the

Fig. 11. Comparison of convergence speed waveforms of switching constant voltage load operating points A (0 V, 10 A) and B (95 V, 4 A) obtained with different look-up table methods under the same setting I-V curve with U_{oc} is 100 V, I_{sc} is 10 A, U_{mp} is 90 V, and I_{mp} is 8 A. (a) The proposed HLFC- R_m I look-up table method. (b) The operating point projection R_m I look-up table method. (c) The UI look-up table method.

HLFC- R_m I look-up table method can still converge to the target working point quickly having a similar dynamic response speed compare to UI look-up table method.

Therefore, from the analysis of the experimental waveforms of Fig. 11 and 12, it can be seen that the HLFC- R_m I look-up table method has the convergence speed close to that of the

Fig. 12. Comparison of convergence speed waveforms under the harshest conditions switching between the short circuit working points A (0 V, 10 A) and open circuit working point C (100 V, 0 A) with the same setting I-V curve of U_{oc} is 100 V, I_{sc} is 10 A, U_{mp} is 90 V, and I_{mp} is 8 A. (a) The proposed HLFC- R_m I look-up table method. (b) The operating point projection R_m I look-up table method. (c) The UI look-up table method.

UI look-up table method, which is close to the ideal switching convergence speed.

C. Arbitrary Given I-V Data Table Simulation Experiment

The actual SSASs need to simulate arbitrary I-V data table

Fig. 13. Experiment waveform of SSAS to simulate the output curve of shaded PV array with HLFC- R_{mI} look-up table method. (a) Given UI data table. (b) Target look-up table curve generated with HLFC- R_{mI} look-up table method. (c) Output steady-state I-V curve.

curves given by the user, such as the shaded PV array. In order to verify that the HLFC- R_{mI} look-up table method can also used to simulate the curves of any given data table, the experiment waveform, Fig. 13, is the output I-V curve with given data table of the shaded PV array, where Fig. 13(a) is the given UI data table curve of the shaded PV array; Fig. 13(b) is the target look-up table curve generated by using HLFC- R_{mI} look-up table method; Fig. 13(c) is the steady-state I-V curve outputting by SSAS.

Comparing with the given UI data table curve, Fig. 13(a), the target impedance-current curve, Fig. 13(b), has a better linearity of all working points, even though the linearization coefficient k_{table} is a constant value (k_{table} is 1). Meanwhile, by comparing Fig. 13(a) and (c), it can be seen that the SSAS can well complete the simulation output of all working points in

the given data table, including the short circuit working point (0 V, 5.6 A), the open circuit working point (45 V, 0 A), and the inflection working point (36 V, 1.5 A).

The experimental results prove that the proposed HLFC- R_{mI} look-up table method is also applicable to simulate arbitrary given I-V data table curves, and can be applied to the actual SSAS equipment easily and conveniently.

IV. CONCLUSION

In this paper, we propose the HLFC- R_{mI} look-up table method to solve the simulation accuracy of the I-V curve with a high tangential slope cannot be realized by the traditional I-V outer loop control method. Further, we also addressed the slow convergence of target points under the working points switching condition in the aerospace application field. For this, the high linearization coefficient and high-speed convergence methods are proposed. Further, the SSAS hardware platform was experimentally verified under the 1-kW multi-level bus tracking architecture. The experimental results show that the proposed HLFC- R_{mI} look-up table method can simulate the I-V curves of any high tangent slopes and its convergence speed is close to that of the UI look-up table method, which is close to the ideal switching convergence speed. In addition, the simulation function of arbitrary I-V curve set by the user can be realized with a satisfied control linearity of the I-V outer loop.

At present, this study has functionally verified the SSAS hardware platform, which can be directly applied to the high-speed solar array simulator device.

APPENDIX

All relevant parameter definitions and descriptions mentioned in this paper are shown in TABLE I.

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TABLE I
DESCRIPTION LIST FOR ALL PARAMETERS

Parameter name	Unit	Description of the parameters meaning
SSAS	-	Space solar array simulator
$R_m I$	-	Impedance-current data table processed by linearization method
RI	-	Impedance-current data table without using linearization method
$R_{m_real-time}$	Ω	The equivalent impedance value calculated by the digital controller during the real-time lookup process using the HLFC- $R_m I$ look-up table method
U_{oc}	V	open circuit voltage
I_{sc}	A	short circuit current
U_{mp}	V	maximum power point voltage
I_{mp}	A	maximum power point current
U_{sas}	V	SSAS output voltage
I_{sas}	A	SSAS output current
R_s	Ω	Intermediate variable in the general exponential mathematical model, in (1)
N	-	Intermediate variable in the general exponential mathematical model, in (2)
a	-	Intermediate variable in the general exponential mathematical model, in (3)
R'_m	Ω	The equivalent impedance with the operating point projection $R_m I$ look-up table method proposed in [20]
U_{sas_sa}	V	The voltage at the output of the SSAS output through the sampling circuit.
U_{ref}	V	The current control reference value for the linear current source unit to control the SSAS output power current.
U_{dc}	V	DC power input voltage of multi-level bus tracking unit
U_{bus}	V	Output bus voltage of multi-level bus tracking unit
Z_L	Ω	Load impedance connected to the SSAS output port
$(dI/dU)_{max}$	A/V	Maximum tangent slope of the I-V setting curve
R_m	Ω	The equivalent impedance with the HLFC- $R_m I$ look-up table method
R_{m_min}	Ω	The minimum equivalent impedance with the HLFC- $R_m I$ look-up table method
R_{m_max}	Ω	The maximum equivalent impedance with the HLFC- $R_m I$ look-up table method
k	-	The linearization coefficient in the equivalent impedance calculation formula of the HLFC- $R_m I$ look-up table method
P_{sas}	W	SSAS output power
U'_{sas}	V	The equivalent output voltage after correcting the origin point of the I-V curve to $(0, k \cdot I_{sc})$
I'_{sas}	A	The equivalent current after correcting the origin point of the I-V curve to $(0, k \cdot I_{sc})$
R_{m_pre}	Ω	The equivalent impedance combining with the optimal linearization coefficient k , but without using optimized fast convergent method.
I_m	-	Intermediate temporary working point of the m-th table look-up cycle during the work point switching convergence process.
P_m	-	Ideal working point on the I-V curve of the m-th table look-up cycle during the work point switching convergence process.
P_{m_pre}	-	Actual working point of the m-th table look-up cycle during the work point switching convergence process.
q	-	The current look-up table period of the digital I-V outer loop.
I_{sas_ref}	A	The control command current value transmitted by the digital I-V outer loop controller to the linear hardware current source.
k_{table}	-	The linearization coefficient used in the arbitrary given I-V data table simulation condition with the HLFC- $R_m I$ look-up table method

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