Method for measuring I-V characteristics of solar cells

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***Abstract** –The key technique for measuring the Ampere-Volt* (I-V) *characteristic of a solar cell is to control the electronic load. In this paper, a new technique for measuring the* I-V *characteristics of solar cells is proposed. The field effect transistor* (FET) *is used to simulate the resistance instead of the slide-wire varistor as the load of the solar cell. The ratio of the load voltage and current is calculated by the multiplying DAC, and the gate of the FET is feedback-controlled to keep the set resistance constant. The resistance of the FET load is only related to the digital quantity input of the D/A, and is not affected by voltage, current and power. For example as 20 work-points, here gives a detailed calculation method for determining work-points, so that the work-points are equally distributed and equiangular on the I-V curve. The experimental results are also given in this paper.*

***Keywords** –Solar cell, Ampere-Volt characteristic, I-V curve, Electronic load, Open voltage, Short current, Maximum power point, Multiplying DAC, Simulation resistor.*

I. INTRODUCTION

The solar cell can be looked as a constant voltage power source or as a constant current power source. In the process of changing the load resistance from an open circuit with an infinite value to a short circuit with a zero resistance value, a pair of data consisting of voltage V and current I on its load resistor is called I-V characteristics. The I-V curve drawn on a plane with the voltage and current as axes is called an I-V characteristic curve (I-V curve). The volt-ampere characteristic curve is an important part of the solar simulator[0], which plays an important role in the analysis of the series resistance, parallel resistance, dark current and spectral response of solar cells[2], Generally measuring I-V characteristics requires a variable load resistor. Controlling electronic loads is a key technology for measuring IV characteristics[5], and often requires fast-changing electronic loads[6]. This paper examines how to control the load resistor, the way to program the voltage and current of work-points, and the method of calculate the load resistance.

II. NORMAL METHOD

Ren Biao of China Northwestern Polytechnical University designed a testing circuit of solar cell I-V characteristic[7], as shown in Fig.1. The current I of the solar cell was converted into a voltage V_I by a feedback resistor R_f, and I can be adjusted with the value of R_f. The changeable resistance R_w can adjust the voltage V of the solar cell, and the floating-ground battery S provides positive and negative bidirectional bias voltages. The disadvantage of this method is that the load resistor cannot be set steadily, and adjusting R_f or R_w alone will cause both V_I and V to change simultaneously.

Peng Kai, China Hefei University of Technology, proposed the measurement method of dynamic capacitor charging and discharging load[8], as shown in Fig.2. The capacitor is used as a load to make the voltage and current change. During charging and discharging of the capacitor, the solar cell's I-V can be measured. The disadvantage is that the work-point cannot be controlled in a stable state, and the short-circuit-current work-point cannot be reached.

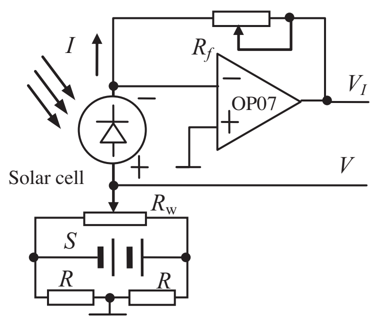

Fig.1 The bias voltage of a floating battery to measure IV characteristics

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He Yufeng of the Institute of Plasma Physics of the Chinese Academy of Sciences uses a precision constant current source as the load of the battery to set the current flowing through the solar cell[9]. The disadvantage is that when the I-V characteristic of the solar cell enters the constant current region, the working point of the voltage cannot be set.

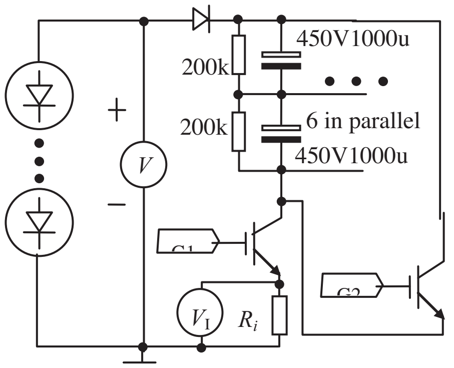


Fig.2 Charge and discharge of dynamic capacitors to measure IV characteristics

In this paper, a programmable-controlled load resistor circuit is designed to overcome the above shortcomings. A stable working point can be set arbitrarily in the constant voltage source region, the constant current source region and the maximum power region on the IV curve. [10]

III. MEASUREMENT METHOD BASED ON PROGRAMMABLE LOAD RESISTOR.

Solar cell I-V characteristic measurement circuit based on programmable load resistor, as shown in Figure 3, It consists of a power supply V_{CC}, a protection resistor R_A, a switch's, or connector's resistances R_{p1} and R_{p2}, a under tested solar cell V_c, a load resistor R_L, and a shunt R_s. The resistance of R_L is realized by the FET, that is, the resistance between the drain D and the source S on FET. The digital input value D_w of the multiplying DAC sets the value of the load resistor, and the negative feedback amplifier A1 controls the gate G to achieve stable value of the R_L. The resistor R_f and the capacitor C_f form a low-pass filter to prevent the feedback loop from self-oscillation, and the period during the load resistor value step should be greater than 5 R_fC_f.

The voltage V_c of the solar cell and the shunt R_s are measured by a 4-wire method in which one pair of positive and negative wires are used to conduct current, and the other pair of positive and negative wires are connected to a differential amplifier to measure voltage and current, respectively. The voltage and current are collected simultaneously, and a pair data of voltage and current are collected each time. As a point on the I-V curve, the acquisition period should match the change speed of the load resistor. The dual-channel data acquisition technology is a general-purpose technology, which will not be described in detail in this paper.

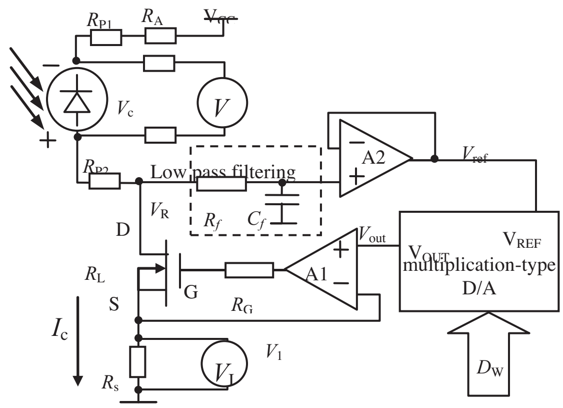


Fig.3 Measurement of IV characteristics based on programmed load resistors

When the negative feedback reaches the equilibrium state, the voltages of the non-inverting terminal and the inverting terminal of A1 are equal, The voltage V_1 on terminal S of FET is equal to the output voltage V_{out} on the multiplying DAC, that is, $V_1=V_{out}$; A2 makes V_R of the terminal D of FET equal to the voltage V_{ref} on the reference voltage terminal of the multiplying DAC, that is, $V_R=V_{ref}$, and the load resistance R_L on the FET is:

$$R_L=(V_R-V_1)/I_c=(V_R-V_1)/(V_1/R_s)=R_s(V_R-V_1)/V_1$$

The relationship between the output voltage V_{out} of the multiply-type D/A and the reference voltage V_{ref} is: $V_{out}=D_wV_{ref}$. Substituting the above formula:

$$R_L=R_s(V_{ref}-V_{out})/V_{out}=R_s(V_{ref}/V_{out}-1)=R_s(1/D_w-1) \quad (1)$$

$$D_w=1/(R_L/R_s+1) \quad (2)$$

The value range of the digital quantity D_w is $0 \le D_w < 1$, the digital quantity D_w is a binary decimal, and the expression for the N-bit D/A is as follows:

$$D_w=(a_{N-1}2^{N-1}+a_{N-2}2^{N-2}+\cdots+a_1 2^1+a_0 2^0)/2^N \quad (3)$$

Where: a_{N-1}, a_{N-2}, $\cdots a_1$, a_0 takes a value of 0 or 1. For example: 12bit multiply-type D/A:
Assuming that:

D/A sets D_w=1000 0000 0000B, D_w=2048/4096=0.5, then $R_L=R_s(1/0.5-1)=R_s$.
D/A sets D_w=0100 0000 0000B, D_w=1024/4096=1/4, then $R_L=R_s(4-1)=3R_s$.
D/A sets D_w=0000 0000 0001B, D_w=1/4096, then $R_L=R_s(4096-1)=4095R_s$.
D/A sets D_w=1111 1111 1111B, D=4095/4096 , $R_L=R_s(4096/4095-1)=(1/4095)R_s$

IV. CALCULATION OF SOLAR CELL'S WORK-POINT

The current I_c flows through the power source V_{CC}, and the solar cell V_c, the protection resistor R_A, the switch's and connector's resistors R_{p1} and R_{p2}, the FET load R_L, and the shunt R_s as loop in series, and finally flow back to the power source from the ground. Ignoring the effects of leakage current at input of meters, the equivalent circuit is shown in Figure 4a), according to Kirchhoff's law.

$$I_c(R_A+R_{p1}+R_{p2}+R_L+R_s)=V_{CC}+V_c=U \tag{4}$$

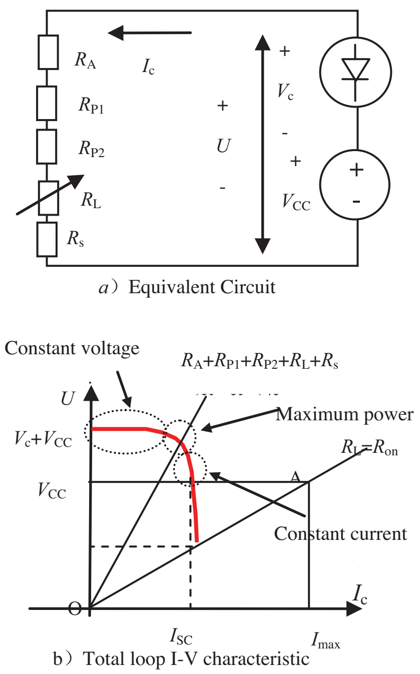


Fig.4 Equivalent circuit of I-V characteristics measurement of solar cells

Taking the voltage as the vertical axis and the current as the horizontal axis, the I-V characteristic of the total potential of the circuit $U=V_{CC}+V_c$ and the current I_c is shown in Fig. 4b). The OA straight line passing through the origin is a state in which the FET is fully turned on, the load resistance $R_L=R_{on}$, and the on-resistance R_{on} is small, and when $V_c=0$, $I_c=I_{max}$. I_{max} is the maximum range of current that can be calculated from known resistance and voltage parameters:

$$I_{max}=V_{CC}/(R_A+R_{p1}+R_{p2}+R_{on}+R_s) \tag{5}$$

The IV characteristic curve of the solar cell is showed as a thick line in Figure 4b). The dotted line portion cannot be set, due to the limitation of the total resistance. The relationship between work-point (V_c, I_c) and R_L is a function as follows:

$$R_L=(V_c+V_{CC})/I_c-(R_A+R_{P1}+R_{P2}+R_s) \tag{6}$$

Where: R_A is the protection resistor, R_{P1} and R_{P2} are the resistance of the switch, wire, and connecter combined, R_L is the FET load, that controlled by the value D_w set by DAC, R_s is the shunt resistor; (I_c,V_c) is the point on the curve, V_{CC} is the supply voltage, here designs 5V power supply on practical applications. Assuming that DAC has 12 bits, it can be seen from equation (1) that R_L can change from (1/4095) R_s to 4095 R_s. Calculate the resistance R of the total loop to obtain the FET load resistance $R_L=R-R_A-R_{P1}-R_{P2}-R_s$.

If the work-point (V_c,I_c) on the right side of the equal (6) is certain on curve, and the other parameters have been designed on the circuit, R_L can be attained. Vice versa, if R_L is set by DAC, then work-point (V_c,I_c) are stable on IV curve.

V. ALGORITHM FOR LOAD RESISTANCE VALUE

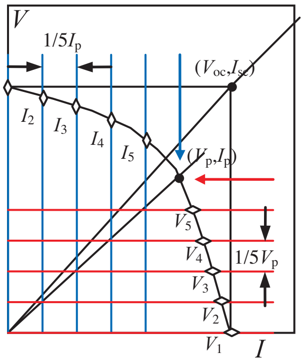
Step 1: The known conditions and requirements:

Predetermine the maximum power point (I_p,V_p) of the solar cell, the open circuit voltage V_{oc} and the short-circuit current I_{sc}, and calculate the load resistance values corresponding to the 20 work-points using these four known parameters. It is required to distribute at least 5 points in each the constant voltage source region and in the constant current source region, and other points should be evenly distributed.

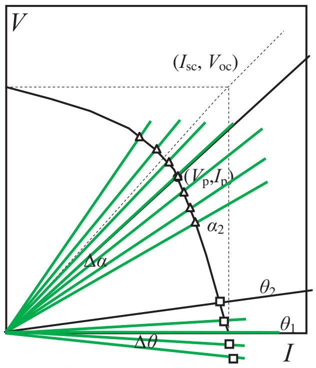
1) The 20 work-points are divided into 4 regions, of which 5 points satisfy the uniform distribution in the constant voltage source region, 5 points satisfy the uniform distribution in the constant current source region, 7 points are satisfied the uniform distribution in the maximum power region, and 3 points are satisfied the

uniform distribution in the short-circuit current region.

2）There are two methods for calculating the work-point on the IV curve of the solar cell: equal interval distribution and equal angle distribution. The constant voltage and constant current regions are equal interval, as shown in Figure 5a). The equal angle distribution is used near the maximum power point, and used near the short-circuit current point, as shown in Fig.5b).



（a）Equal interval distribution



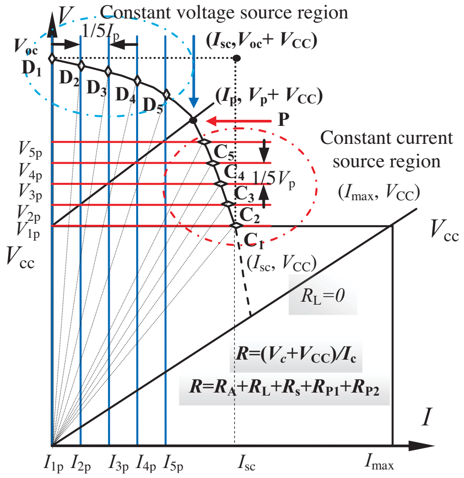
（b）Equal angle distribution

Fig.5 IV characteristics and work-point distribution of solar cells

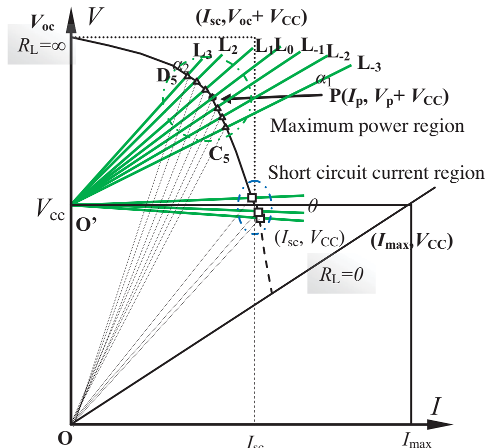
Put the I-V curve of Fig.5 into the total circuit with V_{cc} power supply. The curve is shown in Figure 6, which has the relationship as (6).

Step 2: Equal interval algorithm for constant current source region

Assume that the four parameters I_{sc}, V_{oc}, I_p, and V_p of the I-V characteristic curve of the solar cell are estimated values, and use them as known parameters to find five intersections C_1~C_5 in the constant current source region by using the equal interval method. As long as the intersection work-points, (I_{x1},V_{1p}), (I_{x2},V_{2p}), (I_{x3},V_{3p}), (I_{x4},V_{4p}), (I_{x5},V_{5p}) on the IV curve, and the equal parallel line are calculated, the total loop resistance R can be calculated. $R= V_{ip} /I_{xi}=y/x$ which in turn calculates the value of R_L. The value D_w of DAC is obtained by the equation (2).



（a）Equal interval distribution of constant voltage and current region



（b）Equal angle distribution on maximum power and short circuit current region

Fig.6 I-V curve of the measurement circuit with power supply V_{CC}

However the actual IV curve is unknown. The partial curve in the constant current source region may be replaced by the straight line through two points $P(I_p,V_p+V_{CC})$ and $C_1(I_{sc}, V_{CC})$. In the linear expression of PC_1, x and y represent the current variable and Voltage variable respectively：

$$\frac{x-I_p}{y-V_p-V_{CC}}=\frac{x-I_{sc}}{y-V_{CC}} \tag{7}$$

Step 3: Equal interval algorithm for constant voltage source region.

The known conditions are the same as Step 2. With the equal interval method, find five intersections D1~D2 in the constant voltage source region. Calculate the coordinates (I_{1p},V_{x1}), (I_{2p},V_{x2}), (I_{3p},V_{x3}), (I_{4p},V_{x4}), (I_{5p},V_{x5})

of the intersection on the IV curve and the equal interval parallel line, and then calculate the total resistance value $R=V_{xi}/I_{ip}$, and then attain the value of R_L. However the unknown actual curve equation, approximately replace the constant voltage source segment curve with two straight points $P(I_p,V_p+V_{CC})$ and $D_1(0,V_{oc}+V_{CC})$, PD_1 straight line expression:

Table Ⅰ. Intersection coordinates of five horizontal equal interval lines and straight line PC_1

Serial num	Horizontal straight line equation	Coordinate of the intersections	Total resistance value R
1	$y=V_{CC}$	$x=I_{sc}$, $y=V_{cc}$	$R=V_{cc}\,I_{sc}$
2	$y=\frac{1}{5}V_p+V_{CC}$	$x=\frac{4I_{sc}+I_p}{5}$ $y=\frac{1}{5}V_p+V_{CC}$	$R=y/x$ $I_{x2}=x$ $V_{2p}=y$
3	$y=\frac{2}{5}V_p+V_{CC}$	$x=\frac{3I_{sc}+2I_p}{5}$ $y=\frac{2}{5}V_p+V_{CC}$	$R=y/x$ $I_{x3}=x$ $V_{3p}=y$
4	$y=\frac{3}{5}V_p+V_{CC}$	$x=\frac{2I_{sc}+3I_p}{5}$ $y=\frac{3}{5}V_p+V_{CC}$	$R=y/x$ $I_{x4}=x$ $V_{4p}=y$
5	$y=\frac{4}{5}V_p+V_{CC}$	$x=\frac{I_{sc}+4I_p}{5}$ $y=\frac{4}{5}V_p+V_{CC}$	$R=y/x$ $I_{x5}=x$ $V_{5p}=y$

$$\frac{x-I_p}{y-V_p-V_{CC}}=\frac{x}{y-V_{oc}-V_{CC}} \tag{8}$$

Table Ⅱ. Intersection coordinates of five vertical equal interval lines and PD_1 lines

Serial num	Vertical straight line equation	Coordinate of the intersections	Total resistance value R
1	$x=0$	$x=0$ $y=V_{oc}+V_{CC}$	$R=\infty$
2	$x=\frac{1}{5}I_p$	$x=\frac{1}{5}I_p$ $y=\frac{4(V_{oc}+V_{CC})+(V_p+V_{CC})}{5}$	$R=y/x$ $I_{2p}=x$ $V_{x2}=y$
3	$x=\frac{2}{5}I_p$	$x=\frac{2}{5}I_p$ $y=\frac{3(V_{oc}+V_{CC})+2(V_p+V_{CC})}{5}$	$R=y/x$ $I_{3p}=x$ $V_{x3}=y$
4	$x=\frac{3}{5}I_p$	$x=\frac{3}{5}I_p$ $y=\frac{2(V_{oc}+V_{CC})+3(V_p+V_{CC})}{5}$	$R=y/x$ $I_{4p}=x$ $V_{x4}=y$
5	$x=\frac{4}{5}I_p$	$x=\frac{4}{5}I_p$ $y=\frac{(V_{oc}+V_{CC})+4(V_p+V_{CC})}{5}$	$R=y/x$ $I_{5p}=x$ $V_{x5}=y$

Step 4: Equal Angle Algorithm for Maximum Power Region.

The known conditions are the same as Step2, where the equal angle method is used. In Fig. 6b), between D_5 and C_5, 7 rays are equally distributed in angle, and one ray in the middle should pass the maximum power point P, The size of the adjacent ray angle $\Delta\alpha$ should be 1/8 of the angle between the ray $O'C_5$ and $O'D_5$. As shown in Figure 7. The angle of inclination of the ray passing the point $C_5(I_{x5},V_{5p})$ is $\alpha_1=\text{arctg}[(V_{5p}-V_{CC})/I_{x5}]$, and the inclination angle of the ray passing the point $D_5(I_{5p},V_{x5})$ is $\alpha_2=\text{arctg}[(V_{x5}-V_{CC})/I_{p5}]$, The step size of the equal angle is $\Delta\alpha=(\alpha_2-\alpha_1)/8$. Take a straight line passing through the two points $O'(0, V_{CC})$ and $P(I_p,V_p+V_{CC})$ as the axis of symmetry $O'P=L_0$. The angles between the other 6 rays and L_0 are $-3\Delta\alpha$, $-2\Delta\alpha$, $-\Delta\alpha$, $\Delta\alpha$, $2\Delta\alpha$, $3\Delta\alpha$, the expressions for the 7 straight lines L_{-3}, L_{-2}, L_{-1}, L_0, L_1, L_2, L_3, are:

$$L_0:\quad y=\frac{V_p}{I_p}x+V_{CC}$$

$$L_i:\quad y=x\tan\left(\arctan\frac{V_p}{I_p}+i\Delta\alpha\right)+V_{CC}$$

(i=-3.-2.-1.1,2,3)

Intersected the equal angle ray L_i and the IV curve to obtain the intersection coordinates, and then the total resistance R is obtained, thereby calculating the resistance of R_L. However, the actual IV is unknown. On the right side of L_0, the maximum power section of the IV curve is replaced by the straight line of PC1 in Step 2, and the intersection with L_0,L_{-1},L_{-2}, , and L_{-3} is calculated as:

$$(x_0,y_0)=(I_p,V_p+V_{CC})$$

$$(x_i,y_i)=\left\{\begin{array}{l}\dfrac{I_{sc}V_p}{V_p-(I_p-I_{sc})\tan\left(\arctan\dfrac{V_p}{I_p}-i\Delta\alpha\right)},\\[2ex] \dfrac{I_{sc}V_p\tan\left(\arctan\dfrac{V_p}{I_p}-i\Delta\alpha\right)}{V_p-(I_p-I_{sc})\tan\left(\arctan\dfrac{V_p}{I_p}-i\Delta\alpha\right)}+V_{CC}\end{array}\right\}$$

Where i = 1, 2, 3. The total resistance is $R = y / x$.

On the left side of L_0: replace the IV curve with the PD_1 line. The intersection of the maximum power section and L_1, L_2, L_3, is calculated as:

$$
(x_j, y_j) = \left\{ \begin{array}{l} \dfrac{I_p V_{oc}}{V_{oc} - V_p + I_p \tan\left(\arctan\dfrac{V_p}{I_p} + j\Delta\alpha\right)}, \\ \dfrac{I_p V_{oc} \tan\left(\arctan\dfrac{V_p}{I_p} + j\Delta\alpha\right)}{V_{oc} - V_p + I_p \tan\left(\arctan\dfrac{V_p}{I_p} + j\Delta\alpha\right)} + V_{CC} \end{array} \right\}
$$

Where j = 1, 2, 3. The total resistance is $R=y/x$.

Step 5: Equal Angle Algorithm for Short Circuit Current Region

The known conditions are the same as Step 2. Between the points C_1 and C_2, the angles equated by the point O' are equally divided into three angles, and the angle step $\Delta\theta$ is 1/3 of the angle between the rays O'C_1 and O'C_2, as shown in Fig. 7. The inclination of the ray passing the point $C_2(I_{x1},V_{1p})$ is: θ_2=arctg[$(V_{1p}-V_{CC})/I_{x1}$], The inclination angle of the ray passing the point $C_1(I_{sc}, V_{CC})$is $\theta_1=0$, and the interval angle step $\Delta\theta=(\theta_2-\theta_1)/3$.Taking the O'$C_1$ line as the reference line L_{s0}, the angles between the straight lines L_{s1}, L_{s2}, L_{s3} with L_{s0} are $-2\Delta\theta$, $-\Delta\theta$, $\Delta\theta$ respectively, and the three straight lines should be:

L_{s0}: $y=V_{CC}$

L_{s1}: $y=\tan(-2\Delta\theta)x+V_{CC}$

L_{s2}: $y=\tan(-\Delta\theta)x+V_{CC}$

L_{s3}: $y=\tan(\Delta\theta)x+V_{CC}$

Replace the short-circuit current section of the actual IV curve with the vertical line $x=I_{sc}$, and the expression of the intersection point with the above-mentioned straight lines L_{s1}, L_{s2}, L_{s2} is very simple, directly list the total resistance, respectively, as follows:

$$
R_{s1} = \tan(-2\Delta\theta) + \frac{V_{CC}}{I_{sc}}, \quad R_{s2} = \tan(-\Delta\theta) + \frac{V_{CC}}{I_{sc}}, \quad R_{s3} = \tan(\Delta\theta) + \frac{V_{CC}}{I_{sc}}
$$

VI. TEST RESULTS

The experimental circuit design parameters are: V_{CC} =5V, R_s =2Ω, R_A =3.3Ω. Set the parameters of the solar cell simulator E4360 as follows: (I_{sc},V_{oc}) = (0.5A, 3.3V), (I_p,V_p) = (0.45A, 2.6V), Set the parameters of the solar cell simulator E4360 as follows: (I_{sc},V_{oc}) = (0.5A, 3.2V), (I_p,V_p) = (0.45A, 2.6V), calculate 20 load resistance values according to the formula in Step2~5. To obtain value R_L, and then enter the formula (2) to obtain 20 DAC set values D_w, which are sequentially sent to the multiplying DAC for scanning. After each D_w value is output, the data collector synchronously samples the voltage and current values. Keep D_w unchanged, voltage and current are sampled 200 times and then averaged, the average value is taken as the work-point coordinate of the IV curve, and the measurement result is shown in Fig. 8.

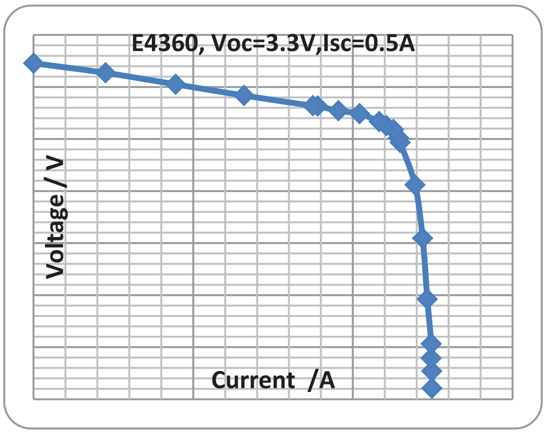


Fig.8 IV curve, and the measurement result

Table III. Measurement data of E4360 at V_{oc}=3.3V, I_{sc}=0.5A, V_p=2.6V, I_p=0.45A

	Voltage/V	Current/A		Voltage/V	Current/A
1	0. 1051	0. 4990	11	2. 6273	0. 4420
2	0. 2683	0. 4990	12	2. 6674	0. 4332
3	0. 3929	0. 4981	13	2. 7425	0. 4084
4	0. 5311	0. 4982	14	2. 7719	0. 3820
5	0. 9603	0. 4933	15	2. 8161	0. 3560
6	1. 5451	0. 4875	16	2. 8193	0. 3500
7	2. 0588	0. 4780	17	2. 9176	0. 2639
8	2. 4656	0. 4593	18	3. 0253	0. 1781
9	2. 5090	0. 4574	19	3. 1357	0. 0903
10	2. 5898	0. 4511	20	3. 2280	0. 0003

VII. CONCLUSION

FET have been widely used for constant voltage sources or constant current sources, and are conventional and mature techniques for use as conditioning and control devices. However, fixing the resistance of the FET to the digital quantity and not changing with voltage, current and power is the innovation of this paper. The principle is simply referred to as the "division feedback principle", that is, the multiplying DAC is used to realizes the division calculation of voltage by current. As long as the negative feedback circuit keeps this quotient stable, the resistance between the D and S terminal of FET can be stabilized. Another power supply, V_{CC}, must be connected in the measurement circuit. The purpose of V_{CC} is to compensate for the shunt resistor, the resistance on wire, switch, connector, the on-resistance of the FET, and the voltage drop across other resistors in the loop. After introducing a power supply, if the voltage is known to be a fixed value, the corresponding DAC setting value can be calculated according to the position of the preset work-point. This paper exemplifies the calculation method of equal interval distribution and equal angle distribution work- point. This method replaces the IV curve with two straight lines. Therefore, the 20 working points in the actual test results are not strictly distributed at equal intervals and equal angles. The actual circuit sets the minimum time for each load resistance up to 40μs, and the minimum scan time of 20 points does not exceed 1ms. The measurement results provided are the best measurements obtained at 40 ms/point. This work has been put into use on the satellite-mounted solar cell space calibration device and has obtained the invention patent authorization by Sipo.

REFERENCES

[1] Edition 2.0 Part 9: Solar Simulator Performance Requirements, IEC 60904-9, 2008.

[2] El-ADAWI M K , Al-NUAIM I A . A method to determine the solar cell series resistance from a single I–V. Characteristic curve considering its shunt resistance—new approach[J]. Vacuum, 2001, 64(1):33-36.

[3] PRIYANKA, LAL M, SINGH S N, et al. Effect of Localized Inhomogenity of Shunt Resistance on the Spectral Response and Dark I-V Characteristics of Silicon Solar Cell[C].IEEE World Conference on Photovoltaic Energy Conversion，IEEE, 2006.

[4] WEI J Y. Influence of Parallel Resistance of Solar Cells on I-V Curve[J]. Journal of Yunnan Normal University(Natural Sciences), 2012, 32(5):19-22.

[5] LIU M, YANG Y Q, YUAN Y F. Electrical Performance Testing Technology for Spacecraft Solar Cell Array[J].Spacecraft Environmental Engineering, 2010, 27(2): 153-156.

[6] KONG F J. Testing of I-V Characteristic Curve of Solar Cell Modules[J]. Sunshine Energy, 2011(4): 54-57.

[7] REB J, ZHENG J B, LIU D F. Automatic Test System for Volt-ampere Characteristics of Solar Cells Based on Sound Card and MATLAB[J]. Journal of Transduction Technology, 2006, 19(2): 447-449. K.

[8] PENG K. Research on field test equipment for solar cell array characteristics [D]. Hefei University of Technology, 2008.

[9] HE Y F, WENG J, CHEN SH H, et al. Development and analysis of voltammetric characteristics test system for multi-channel DSCs[J]. Journal of Solar Energy, 2006, 27(2): 126-131.

[10] LIU M, et al. A method on measuring I-V characteristic of solar cell and circuit [P]. China Patent, ZL 201610703036.5, www.sipo.gov.cn

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