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Short communication

An electronic load for testing photovoltaic panels

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Abstract

The characteristics of photovoltaic (PV) panels in the field conditions are to be obtained using a fast varying load. The paper presents a simple electronic load for testing a set of PV panels using linear metal oxide field effect transistors (MOSFETs). The proposed test set up gives the current versus voltage and power versus voltage characteristics of PV panels by quickly scanning the load. Design equations giving the MOSFET rating, and gate voltage range for obtaining a specified portion of the PV panel characteristics are derived. With additional signal processing, the maximum power available from the panels and the corresponding current and voltage values are also obtained. Experimental waveforms obtained on the test circuit are presented.

Keywords: Photovoltaic panel; *I–V* characteristic; Linear MOSFET; Maximum power point

1. Introduction

The current versus voltage (*I–V*) characteristics of PV panels are used in the design of power converter systems and the efficient harvesting of solar power. The characteristics of the PV panel under selected operating conditions are provided by the manufacturer and they are obtained under controlled light/temperature conditions in a laboratory environment [1,2]. Because of the quickly and randomly varying field conditions, it is difficult to reproduce the characteristics of individual or group of PV panels. To overcome the above problem, one has to vary the load (resistance) over the entire range in a very short time. In addition to the *I–V* characteristic, there is a need to calculate the maximum power available from the panel(s) and the voltage and current corresponding to the maximum power point (MPP). The linear MOSFET can be used as an electronic load to test the PV panel [3]. The potential advantage of the electronic load is the fast variation (scanning) of the equivalent load resistance. Commercial systems for testing PV panels under field conditions are available but they are computer controlled and are very expensive.

The paper describes a test circuit that uses a linear MOSFET to obtain the current versus voltage and power versus voltage characteristics of a PV panel or a group of PV panels. It is also possible to get the maximum power, and the values of voltage and current at which the power is maximum. Design equations for the voltage, current, and power ratings of the linear MOSFET and the range of gate voltage needed for testing a given panel are obtained. Experimental waveforms obtained on PV panels using the test circuit are given.

2. Theoretical analysis

The power circuit of a PV panel loaded by a linear MOSFET M and a drain resistance R_D is shown in Fig. 1. The operating point of the MOSFET is determined by: (a) the characteristics of the PV panel, (b) the characteristics of the MOSFET, and (c) the circuit connection. All the voltages and current in the circuit can be determined by solving the equations representing the three groups. First the characteristics of a MOSFET are described by [4]:

$$I_D = K_N(V_{GS} - V_t)^2 \quad \text{for constant current region} \qquad (1)$$

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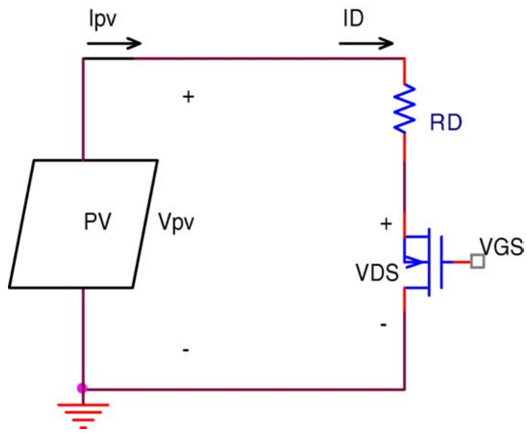

Fig. 1. Basic power circuit.

$$I_D = K_N(2(V_{GS} - V_t)V_{DS} - V_{DS}^2) \quad \text{for ohmic region} \tag{2}$$

where K_N is the device constant, V_t the threshold (gate) voltage, V_{GS} the gate-source voltage, V_{DS} the drain-source voltage, and I_D the drain current of the MOSFET. The approximate equation for a PV panel can be written as

$$I_D = I_{PV} = I_{SC} - I_S\, e^{KV_{PV}} \tag{3}$$

where V_{PV} is the voltage across the PV panel, I_{PV} the output current of the PV panel which is equal to I_D, I_{SC} the short-circuit current, I_S the dark-saturation current of the PV panel and K is a constant which depends on the temperature and cell arrangement in the panel [5]. The series resistance of the panel R_S is neglected in Eq. (3) and the exact equation can be found in [5]. The following equation can be written for the circuit:

$$V_{PV} = V_{DS} + I_D R_D \tag{4}$$

When the MOSFET is working in the constant current region $((V_{GS} - V_t) < V_{DS})$, Eqs. (1), (3) and (4) hold. When the MOSFET is working in the ohmic region $((V_{GS} - V_t) > V_{DS})$, Eqs. (2)–(4) hold. If the PV characteristic, the MOSFET characteristics and R_D are all given, the operating point of the MOSFET is determined by the value of V_{GS}. By sweeping V_{GS} in the appropriate range, the operating point of the MOSFET can be changed, which also drives the operating point of the PV panel to move along its *I–V* characteristic curve. This process is illustrated in Fig. 2 which shows the load curves (nonlinear) for the MOSFET drawn for different values of R_D and the characteristics of the MOSFET. The load curve is obtained by combining Eqs. (3) and (4). While V_{GS} varies from V_{GS1} to V_{GS2}, the operating point of the MOSFET moves from Q_1 to Q_2, hence the characteristic of the PV panel between Q_1 (I_1) and Q_2 (I_2) is traced.

It should be noted that I_{SC} is equal to I_{PV} (or I_D) when $V_{PV} = 0$ and not when $V_{DS} = 0$. The value of I_D when $V_{DS} = 0$ is denoted as I_{PVL}, which is lower than I_{SC}. When $R_D = 0$, the load curve becomes the *I–V* characteristic of the PV panel with $V_{PV} = V_{DS}$, and I_{PVL} approaches I_{SC}. After locating the operating point, say Q_2, the value of V_{PV} is obtained by drawing a straight line with a slope $-1/R_{D1}$ through Q_2 as shown in Fig. 2. The point at which this line intersects the *X*-axis is V_{PV}.

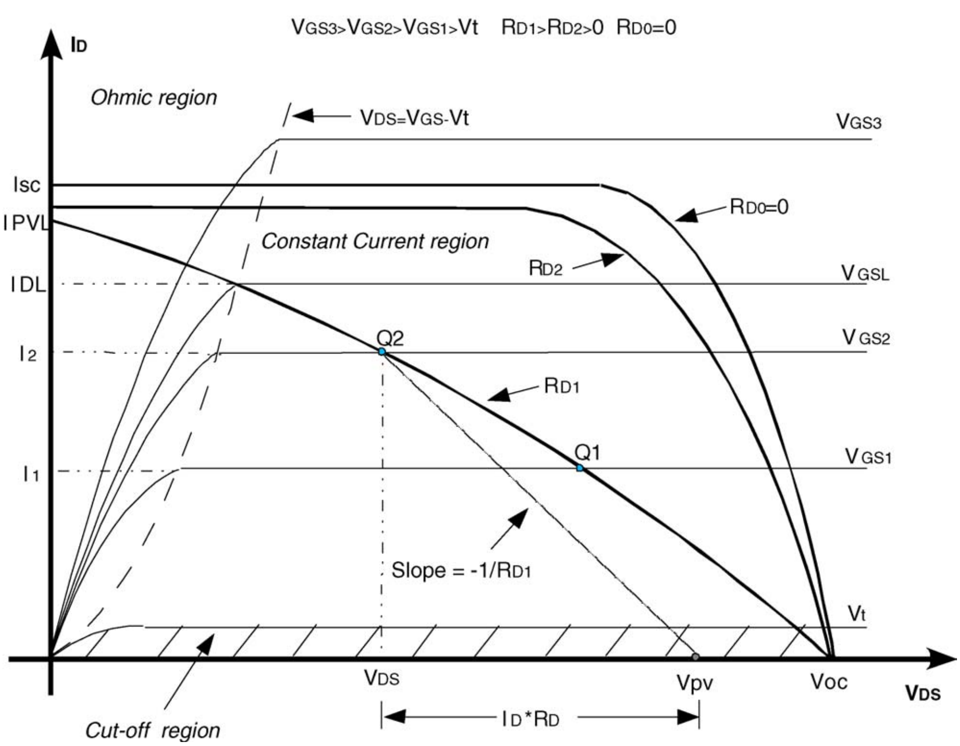

Fig. 2. MOSFET characteristics and load curves.

When V_{GS} is increased from 0 V, the MOSFET will stay OFF until V_{GS} exceeds the threshold voltage V_t. After that, the MOSFET will enter the constant current region and continue to work in that region until it reaches a point where $V_{GS} = V_{GSL}$ which is equal to $V_{DS} + V_t$. The corresponding value of I_D is denoted as I_{DL}. The values of V_{GSL} and I_{DL} are obtained by solving Eqs. (5) and (6) which are obtained by substituting $V_{GS} = V_{GSL}$ in Eqs. (1) and (3) as

$$I_{DL} = K_N V_{GSL}^2 \quad (5)$$

$$I_{DL} = I_{SC} - I_S\, e^{K(V_{GSL} - V_t + I_{DL} R_D)} \quad (6)$$

For a given R_D, the maximum power dissipated by the MOSFET while loading the PV panel should be smaller than its power rating. If P_M is the power dissipated by the MOSFET at any operating point with a given value of R_D and P_{PV} the power supplied by the PV panel, then we have:

$$P_M = P_{PV} - I_D^2 R_D \quad (7)$$

Then P_M can be expressed as

$$P_M = I_{PV} V_{PV} - I_{PV}^2 R_D \quad (8)$$

Substituting for I_{PV} from (3) in (8), we get

$$P_M = -R_D I_{SC}^2 + I_{SC} V_{PV} + I_S (2 R_D I_{SC} - V_{PV})\, e^{K V_{PV}} - R_D I_S^2\, e^{2 K V_{PV}} \quad (9)$$

The derivative of P_M with respect to V_{PV} is given by

$$P'_M = I_{SC} + I_S (2 K R_D I_{SC} - 1 - K V_{PV})\, e^{K V_{PV}} - 2 K R_D I_S^2\, e^{2 K V_{PV}} \quad (10)$$

$P'_M = 0$ when P_M is maximum (equal to P_{MMAX}). Equating (10) to zero and solving for V_{PV} and substituting back in (9), we get the maximum power that will be dissipated by the MOSFET for a given R_D. Using the same process, the value of R_D that has to be used to provide enough protection for the MOSFET can also be calculated. A higher value of R_D reduces the power dissipated by the MOSFET but this will limit the range of PV characteristic that can be covered by the electronic load. After the value of R_D is determined, we need to choose the range of V_{GS} that can cover a selected (significant) portion of the PV panel characteristic. The variation of the power supplied by the PV panel and the ones dissipated by the MOSFET and the resistance R_D are shown in Fig. 3. For a given R_D, the lower limits on V_{PV} and I_{PV} are also shown in the figure. Including the series resistance of the PV panel, the output power will be slightly less and the power rating of the MOSFET to be used will also be correspondingly lower.

The relationships between (a) the maximum gate voltage V_{GSMAX} and the corresponding panel current I_{PV} (I_D) (maximum) and panel voltage V_{PV} (minimum) and (b) the minimum gate voltage V_{GSMIN} and the corresponding panel current I_{PV} (I_D) (minimum) and the panel voltage V_{PV} (maximum) can be obtained as follows.

2.1. I_{PVMAX} and V_{PVMIN}

If $V_{GSMAX} < V_{GSL}$, I_{PVMAX} will occur in the constant current region of the MOSFET which gives:

$$I_{PVMAX} = K_N (V_{GSMAX} - V_t)^2 \quad (11)$$

$$V_{PVMIN} = \frac{1}{K} \ln \left[\frac{I_{SC} - K_N I_{PVMAX}^2}{I_S} \right] \quad (12)$$

Given V_{GSMAX}, the value of I_{PVMAX} can be calculated from (11) and that of V_{PVMIN} is calculated from (12).

If $V_{GSMAX} \geq V_{GSL}$, I_{PVMAX} will occur in the ohmic region of the MOSFET and is described by the following equations:

$$I_{PVMAX} = I_{SC} - I_S\, e^{K(V_{DSMIN} + I_{PVMAX} R_D)} \quad (13)$$

$$I_{PVMAX} = K_N [2 (V_{GSMAX} - V_t) V_{DSMIN} - V_{DSMIN}^2] \quad (14)$$

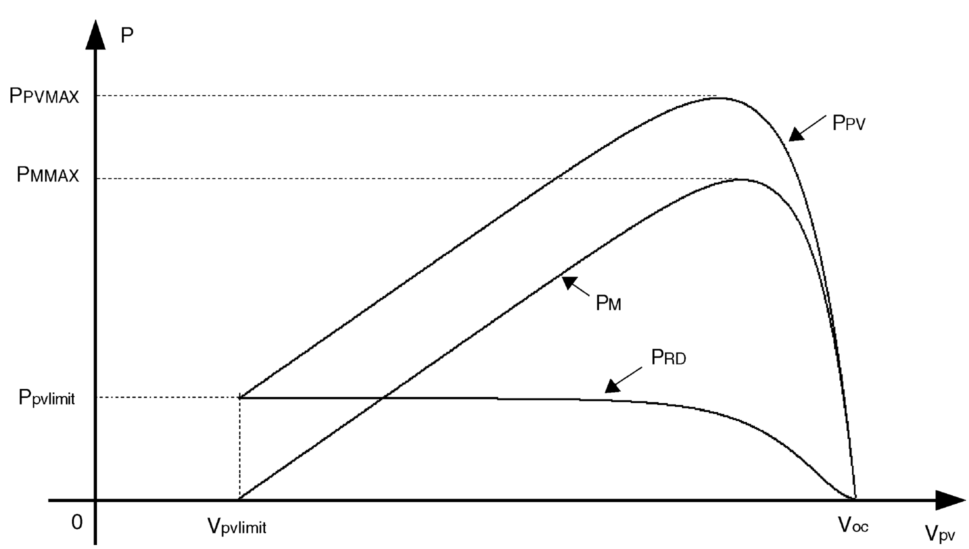

Fig. 3. Plot of PV power and MOSFET power.

Given the values of R_D and V_{GSMAX}, the value of I_{PVMAX} is calculated by solving (13) and (14). Using the value of I_{PVMAX}, the value of V_{PVMIN} is calculated from (12).

2.2. I_{PVMIN} and V_{PVMAX}

If $V_{GSMIN} \geq V_t$, I_{PVMIN} will occur in the constant current region of the MOSFET which gives

$$I_{PVMIN} = K_N(V_{GSMIN} - V_t)^2 \tag{15}$$

$$V_{PVMAX} = \frac{1}{K} \ln\left[\frac{I_{SC} - K_N I_{PVMIN}^2}{I_S}\right] \tag{16}$$

If $V_{GSMIN} < V_t$, the MOSFET will be in the cut-off region giving $I_{PVMIN} = 0$, and $V_{PVMAX} = V_{OC}$.

3. Determination of device parameters

The analysis of Section 2 uses several parameters both of the PV panel and the MOSFET. The parameters K_N and V_t can be taken or calculated from the manufacturer's data sheet for the linear MOSFET.

The typical characteristics of a PV panel given by the manufacturer usually include the following data measured under the standard reporting condition [6]: V_{mp} (voltage at MPP), I_{mp} (current at MPP), I_{SC} (short-circuit current), and V_{OC} (open-circuit voltage). The values of I_S and K are usually not given by the manufacturer directly and they can be calculated as follows.

Rewriting (3), we get:

$$KV_{PV} = \ln\left[\frac{I_{SC} - I_{PV}}{I_S}\right] \tag{17}$$

The power output from the PV panel is given by

$$P_{PV} = V_{PV} I_{PV} \tag{18}$$

From (18), the following equation can be written:

$$e^{KP_{PV}} = e^{KV_{PV}I_{PV}} \tag{19}$$

From (17) and (19), the value of KP_{PV} is obtained as

$$KP_{PV} = I_{PV} \ln\left[\frac{I_{SC} - I_{PV}}{I_S}\right] \tag{20}$$

For getting the coordinates of the MPP, (20) is differentiated with respect to I_{SC} and equated to zero giving:

$$\frac{d(KP_{PV})}{dI} = \ln\left(\frac{I_{SC} - I_{PV}}{I_S}\right) - \frac{I_{PV}}{I_{SC} - I_{PV}} = 0 \tag{21}$$

Combining (17) and (21), we get:

$$KV_{mp} = \frac{I_{mp}}{I_{SC} - I_{mp}} \tag{22}$$

The value of K can be calculated from (22). After getting the value of K, the value of I_S can be calculated as

$$I_S = \frac{I_{SC} - I_{mp}}{e^{KV_{mp}}} \tag{23}$$

Oftentimes, a PV system will have a number of individual solar panels connected in series and/or parallel. For a PV system that has m panels in series in a row and n rows in parallel, the equivalent values of I_{SC}, V_{OC}, I_S, and K are given by: $V_{OCtotal} = mV_{OC}$; $I_{SCtotal} = nI_{SC}$; $K_{total} = K/m$; $I_{Stotal} = nI_S$ [5].

4. Calculation example

An electronic load with the linear MOSFET APL501J is set up to test a PV array with five SX-120 solar panels connected in series. From the datasheet of APL501J [3], $V_t = 2$–4 V, $I_D = 43$ A, $V_{GS} = 8$ V and these data yield $K_N = 1.8125$–$7.25\ \mathrm{A\,V^{-2}}$. In calculating the range of gate voltage, the worst case value of $V_t = 4$ V is used.

For the PV array, the parameters are: $I_{SC} = 3.87$ A; $V_{OC} = 205.5$ V; $V_{mp} = 168.5$ V, $I_{mp} = 3.56$ A [6]. The values of K and I_S are calculated from (22) and (23) as: $K = 0.0682\ \mathrm{V^{-1}}$; $I_S = 3.275\ \mu$A.

Using the analysis of Section 2, the following results are obtained: $V_{GSL} = 5.1$ V, $V_{GSMAX} = 5.2$ V, and $P_{MMAX} = 476.71$ W when $R_D = 10\ \Omega$. With V_{GS} varying from 0 to 5.2 V, $I_{PVMAX} \approx 3.87$ A and $V_{PVMIN} \approx 0$ V.

This indicates that an electronic load system using APL501J as the active element and a drain resistance $R_D = 10\ \Omega$ will be able to cover the whole I–V characteristics of the PV array with a V_{GS} varying from 0 to 5.2 V.

5. Experimental set up and results

The block diagram of the test set up for the PV panel is shown in Fig. 4. Circuit blocks for sensing and processing the output voltage and current of the PV panel are added to the power circuit of Fig. 1. The linear MOSFET is driven by a low frequency scan signal with an amplitude large enough to cover the complete range of PV panel characteristic. The threshold voltage of a MOSFET decreases almost linearly as the junction temperature increases [7]. Hence, a separate feedback is added to the MOSFET in order to stabilize the drain current. The feedback also protects the MOSFET against overcurrent. Several MOSFETs can be operated in parallel to handle higher output current from an array with several PV panels [3]. Linear MOSFETs with voltage rating up to 1000 V and power rating up to 520 W are available. As long as the total voltage of the series connected string is less than 1000 V, a single linear MOSFET can be used to load the string. Strings with higher voltage need more than one MOSFET connected in series which might require additional equalizing network. The output voltage and current of the PV panel (V_{PV} and I_{PV}) are sensed using the potential

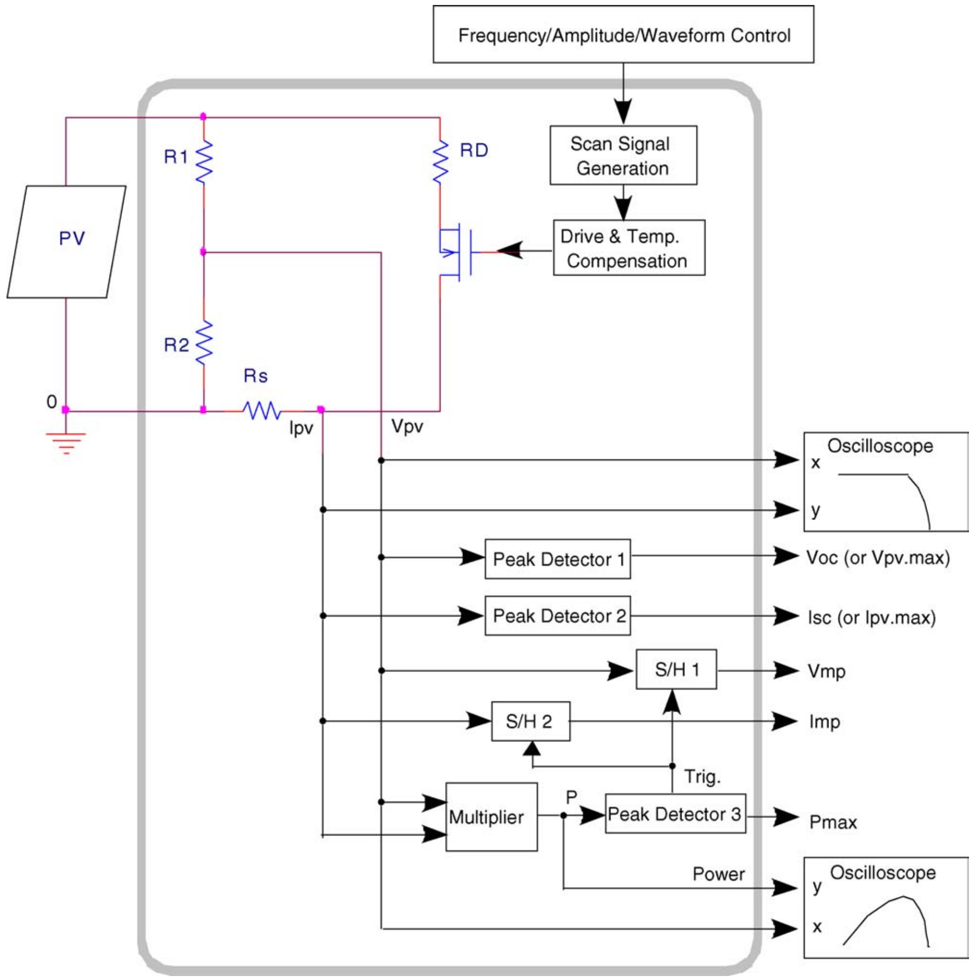

Fig. 4. Block diagram of PV testing unit.

divider (R_1 and R_2) and the sensing resistor R_S respectively. The outputs are fed to the *X* and *Y* inputs of the oscilloscope for displaying the *I–V* characteristic of the PV panel. The values of V_{OC} and I_{SC} are obtained using two peak detectors (Peak-Detector 1 and Peak-Detector 2) [8].

The signals representing V_{PV} and I_{PV} are multiplied using a multiplier to get the instantaneous power output of the PV panel. The power can be applied to a second *Y* channel of the oscilloscope to display the power versus voltage characteristic. During each cycle of variation of the gate signal, the

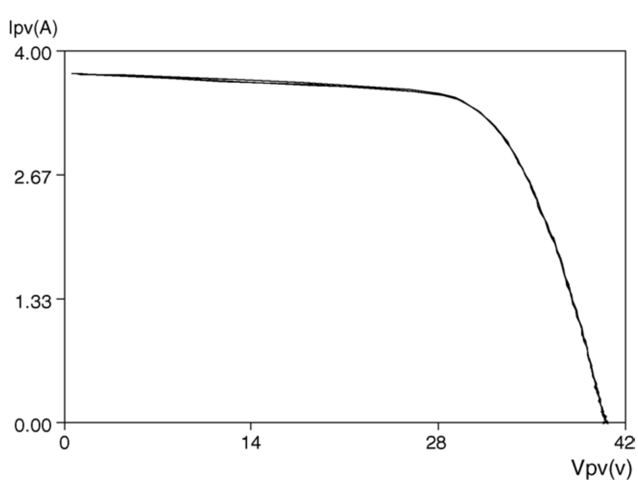

Fig. 5. Experimental current vs. voltage (*I–V*) characteristic of PV panel.

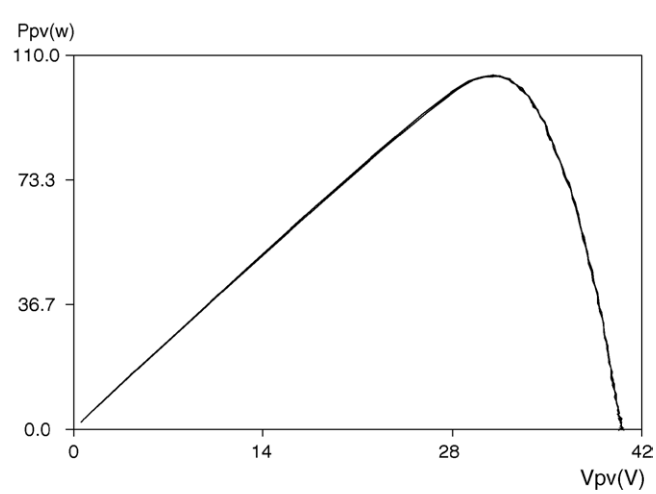

Fig. 6. Experimental power vs. voltage characteristic of PV panel.

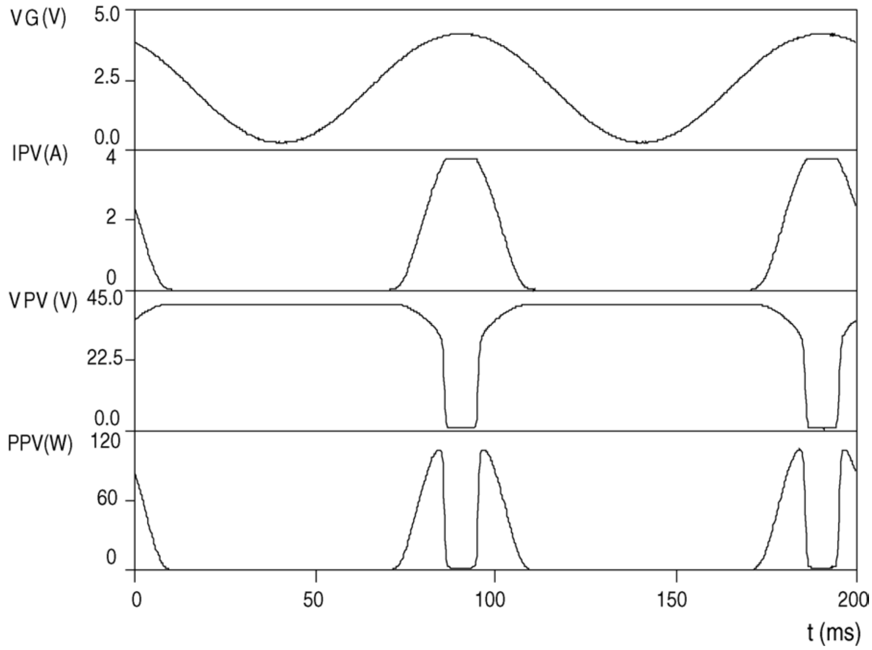

Fig. 7. Experimental waveforms of gate signal, PV current, voltage, and power.

power has two peaks, one during the increasing portion and the other during the decreasing portion. A third peak detector is used to capture the peak power P_{MAX}. The coordinates of the MPP are obtained by sampling the voltage and current variables at the MPP and holding the signal. The output of Peak-Detector 3 is used to obtain the necessary sampling pulse for the sample/hold blocks S/H 1 and S/H 2. The details of the electronic circuit are not given for want of space.

The 120 W PV panel was loaded using a linear MOSFET. The tests were conducted in the month of January 2005 in Fargo which has a latitude of about 45°. The temperature was around −10 °C and there was below-average illumination. The experimental current versus voltage (*I–V*) characteristic obtained is shown in Fig. 5 and the corresponding power versus voltage characteristic is shown in Fig. 6. The trace obtained during flyback (voltage decreasing) almost coincides with the trace obtained during forward travel (voltage increasing). The maximum value obtained in our experiment is around 110 W. The lower value is due to the reduced illumination. The mounting angle of the panels was also not set at the optimum value. The experimental waveforms of the gate voltage and those of the current, voltage, and power drawn from the PV panel are shown in Fig. 7.

6. Conclusions

The paper presents an electronic load and instrumentation scheme for testing PV panels. A linear MOSFET serves as an electronically controlled load that moves the operating point of the PV panel over the entire *I–V* characteristic. In addition to the current versus voltage and power versus voltage characteristics, the circuit provides the values of the open circuit voltage, short-circuit current, peak power, and the corresponding voltage and current. The ratings of the MOSFET to be used in testing one or more panels in series/parallel configurations are also calculated. The test set up is useful in getting the characteristics of the PV panel in the field conditions.

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