Solar Energy Collector Gain Digital Electronic Meter

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Abstract
This paper introduces the design and theory of a digital meter for measuring the total useful solar energy gain of a flat-plate collector. This is an important parameter of the collector involved in determining the efficiency. Measurement is carried out in terms of the collector fluid inlet temperature $T_i$, the fluid outlet temperature $T_o$, and the mass flow rate $m^*$ of the working fluid flowing through the collector. Voltages representative of the variable parameters are assessed and processed using a non-linear analog to digital converter (ADC) and voltage to frequency convertor (VFC) to produce a digital number representative of the solar collector gain.

Keywords: solar energy, digital meter, frequency convertor, collectors, electronic meter.

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الخلاصة
يقدم هذا البحث تصميم ونظرية عدد رقمي لقياس الطاقة الشمسية المفيدة من جامع لوحة مسطحة. وهذا هو العامل المهم من الجامع في تحديد الكفاءة. يتم القيام من حيث درجة حرارة السائل الداخلة للجامع $T_i$, ودرجة حرارة مقدس السائل $T_o$, وมวล التنفقي الشامل $m^*$ من السوائل العاملة التي تتنفس من خلال الجامع. يتم تقييم ومعالجة الفولتية الممثالة (VFC) للمعامل المتغيرة باستخدام محول تناظري غير خطئي إلى المحول الرقمي (ADC) والمحول الفولتية إلى تردد (VFV). لنتائج رقم رقمي يتم الكسب لجامع الطاقة الشمسية.

الكلمات المفتاحية: الطاقة الشمسية، العداد الرقمي، محول التردد، جامع الطاقة، العداد الإلكتروني

Introduction
A solar collector is the essential item of equipment which transforms solar radiant energy to some other useful energy form. [1] The principle application of these units are in solar water heating systems, while potential uses include building heating and air conditioning and many domestic requirements. Flat-plate collectors can be designed for applications requiring energy delivering at moderate temperature up to perhaps 100 C° above ambient temperature. Figure (1) shows the basic flat-plate solar energy collector. In order to determine the goodness of the performance and efficiency of the flat plate collector it is necessary to make available an important parameter. It is the total useful solar energy gain of the collector. It can be written as:[2]

$$ Q_u = (m^* C_p)(T_o - T_i) \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (1) $$

Where

\[ Q_u \rightarrow \text{The total useful energy gain of the collector} \]

\[ m^* \rightarrow \text{The mass flow rate of the collector working fluid} \]

\[ C_p \rightarrow \text{The specific heat of the working fluid} \]
Outlet fluid temperature
Inlet fluid temperature

Also we have,

\[ m = k \frac{P_s \Delta P}{T_s} \]  

Where,

K \rightarrow a constant

\( P_s \) \rightarrow Fluid static pressure

\( \Delta P \) \rightarrow Fluid volumetric flow rate

\( T_s \) \rightarrow Fluid static temperature

This paper introduces the design and theory of a digital meter for measuring the flat plate solar energy collector gain. Five voltages \( V_1, V_2, V_3, V_4 \) and \( V_5 \) are developed, via five transducers, representative of \( T_0, T_i, P_s, \Delta P \) and \( T_s \) respectively.

\[ Q_u \propto (V_2 - V_1) \sqrt{\frac{V_3 V_4}{V_5}} \]  

**Figure (1)** A cross-section of a basic flat plate solar collector.

Those voltages are processed using a nonlinear ADC and VFC to produce digital number representative of the collector gain given in term of voltages by proportionality equation as,

**Figure (2)** A block diagram of the transducers arrangement of the collector gain meter.
Theory and operation

Figure (3) shows a schematic diagram of the flat-plate solar collector gain meter. At \( t = t_o \), the control signal is applied to the system. This signal discharges all the integrating capacitors and also reset the counter to count zero. At first, the voltages \(-V_5\) and \( V_4 \) are applied to the input of integrators \( I_1 \), and \( I_2 \), respectively. The output of the integrators \( I_1 \) is a ramp-up voltage given by:[4]

\[
V_a = -\frac{1}{R_1C_1} \int_{t_0}^{t} V_5 dt = \frac{V_5}{R_1C_1} (t - t_0) \quad \ldots \ldots (4)
\]

And that of \( I_2 \) is,

\[
V_b = -\frac{1}{R_2C_2} \int_{t_0}^{t} V_4 dt
= \frac{-V_4}{R_2C_2} (t - t_0) \quad \ldots \ldots (5)
\]

At \( t = t_0 \), \( V_a \) becomes equal to \( V_3 \).

\[
V_a(t_1) = V_3 = \frac{V_5}{R_1C_1} (t_1 - t_0)
\]

\[\therefore t_1 - t_0 = R_1C_1 \frac{V_3}{V_5} \quad \ldots \ldots (6)\]

Meanwhile, \( V_b(t_1) \) is equal to,

\[
V_b(t_1) = \frac{-V_4}{R_2C_2} (t - t_0)
= \frac{R_1C_1 V_3 V_4}{R_2C_2 V_5} \quad \ldots \ldots (7)
\]

At this moment a positive reference voltage is applied to the input of the integrator \( I_1 \), while the difference \( V_a - V_3 \) is applied to the input of the integrator \( I_2 \).

For \( t > t_1 \)

\[
V_a = V_3 - \frac{1}{R_1C_1} \int_{t_1}^{t} V_4 dt
\]

\[= V_3 - \frac{V_r}{R_1C_1} (t - t_1) \quad \ldots \ldots (8)\]

And,

\[
V_b = V_b(t_1) - \frac{1}{R_2C_2} \int_{t_1}^{t} (V_a - V_3) dt
= \frac{R_1C_1 V_3 V_4}{R_2C_2 V_5} + \frac{1}{R_2C_2} \int_{t_1}^{t} \frac{V_r}{R_1C_1} (t - t_1) dt
= \frac{R_1C_1 V_3 V_4}{R_2C_2 V_5} + \frac{V_r}{2(R_1C_1)(R_2C_2)} (t - t_1)^2 \quad \ldots (9)
\]

At \( t = t_2 \), \( V_b \) becomes equal to zero.

\[
V_b(t_2) = 0 = \frac{R_1C_1 V_3 V_4}{R_2C_2 V_5} + \frac{V_r}{2(R_1C_1)(R_2C_2)} (t_2 - t_1)^2
\]

\[\therefore t_2 - t_1 = R_1C_1 \frac{2}{V_r} \frac{V_3 V_4}{V_5} \quad \ldots \ldots (10)\]

The counter is allowed to count during the interval \( t_2 - t_1 \) with a clock frequency, \( f_o \), which is the output frequency of the VFC, given by,[5]

\[
f_o = k_f (V_2 - V_1) \quad \ldots \ldots (11)\]

Where, \( k_f \) is the constant of the conversation and \( V_2 - V_1 \) is the input voltage of the VFC.

We have

\[
N_{t_2} = \frac{(t_2 - t_1)}{k_f} f_o
= R_1C_1 k_f \sqrt{\frac{2}{V_r}} \frac{V_3 V_4}{V_5} (V_2 - V_1)
= k \sqrt{\frac{V_3 V_4}{V_5}} (V_2 - V_1) \quad \ldots \ldots (12)
\]

Where, \( N_{t_2} \) is the final on the counter at the end of the interval \( t_2 - t_1 \).

\[k = constant = R_1C_1 k_f \sqrt{\frac{2}{V_r}} \]

Thus, \( N_{t_2} \) is proportional to the solar collector gain.
Figure (3) Schematic diagram of the flat-plate solar collector gain digital meter.

**Circuit Operation**

Figure (4) shows the complete circuit diagram of the solar-collector gain digital meter. Figure 5 shows the timing diagram of the meter.[6]

The start signal is applied at \( t = t_0 \), this signal closes \( S_3 \) and \( S_4 \), momentarily, thus disc arching the capacitors \( C_1 \) and \( C_2 \), respectively, also, the counter and the D-flip are reset.[7]

The zero logic of \( Q \) switches the SPDT analogue switches \( S_1 \) and \( S_2 \) to the position 1. The integrator output voltages are given by,

\[
V_a = -\frac{1}{R_1C_1} \int_{t_0}^{t} V_5 \, dt = \frac{V_5}{R_1C_1} (t - t_0) \quad (13)
\]

And

\[
V_b = -\frac{1}{R_2C_2} \int_{t_0}^{t} V_4 \, dt = -\frac{V_4}{R_2C_2} (t - t_0) \quad (14)
\]

At \( t = t_1 \), \( V_a \) became equal to \( V_3 \). The output of the capacitor \( C_1 \) changes state from high to low logic. This negatively going edge triggers the d-type flip flop, setting \( Q \) to logic 1. [8]

Figure (4) Complete Circuit Diagram of the flat Plate Solar collector gain digital meter
The high logic level on Q switches S1 and S2 to position 2. As the output comparator C2 is already high, the high logic level of Q enables the AND gate. The counter starts counting just at $t = t_1$. We have,[9]

$$V_a(t_1) = V_3 = \frac{V_5}{R_1C_1} (t_1 - t_0) \ldots \ldots \ldots (15)$$

$$\therefore t_1 - t_0 = R_1C_1 \frac{V_3}{V_5}$$

And $V_b(t_1) = \frac{V_5}{R_2C_2} (t_1 - t_0)$

$$= -\frac{R_1C_1}{R_2C_2} \frac{V_4V_5}{V_5} \ldots \ldots \ldots \ldots \ldots \ldots \ldots (16)$$

For $t > t_1$, we have,

$$V_a = V_a(t_1) - \frac{1}{R_1C_1} \int_{t_1}^{t} V_rdt$$

$$= V_3 - \frac{V_r}{R_1C_1}(t - t_0) \ldots \ldots \ldots \ldots \ldots \ldots \ldots (17)$$

$$V_b = V_b(t_1) - \frac{1}{R_2C_2} \int_{t_1}^{t} V_cdt$$

Where

$$V_c = V_a - V_3$$

$$= -\frac{V_3}{R_1C_1}(t - t_0) \ldots \ldots \ldots \ldots \ldots \ldots \ldots (18)$$

$$V_b = \frac{R_1C_1}{R_2C_2} \frac{V_3V_4}{V_5} + \frac{V_r}{2(R_1C_1)(R_2C_2)}(t - t_1)^2$$
At \( t = t_2 \), \( V_b \) become equal to zero.

\[
V_b(t_2) = 0 = \frac{R_1C_1}{R_2C_2} \frac{V_3V_4}{V_5} \\
\quad + \frac{V_r}{2(R_1C_1)(R_2C_2)}(t_2 - t_1)^2
\]

\[ \therefore t_2 - t_1 = R_1C_1 \frac{2}{V_r} \frac{\sqrt{V_3V_4}}{\sqrt{V_5}} \] \hspace{1cm} \text{(19)}

The comparator \( C_2 \) changes state from high to low. Counting is ceased and the final number on the counter is:[10]

\[ N_{t_2} = (t_2 - t_1)f_o \] \hspace{1cm} \text{(20)}

Where,

\( N_{t_2} \) the number on the counter at the end of the interval \( t_2 - t_1 \).

\( f_o \) is the output frequency of the VFC , given by

\[ f_o = k_f(V_2 - V_1) \] \hspace{1cm} \text{(21)}

Where ,

\( k_f \) is the conversion constant of the VFC.

Thus,

\[ N_{t_2} = R_1C_1 k_f \frac{2}{V_r} \sqrt{\frac{V_3V_4}{V_5}} (V_2 - V_1) \]

\[ = k \sqrt{\frac{V_3V_4}{V_5}} (V_2 - V_1) \] \hspace{1cm} \text{(22)}

\[ k = R_1C_1 k_f \frac{2}{V_r} = \text{constant} \]

A proper adjustment of the value of \( k \), \( N_{t_2} \) is obviously a representative of the solar energy gain.[11]

**Results**

The circuit of fig 4 was tested for different values of the inputs. Figure 6 shows linearity of the system with \( V_3 \) equals \( V_4 \) for different values of \( V_5 \). Figure 7 shows the square routing non-linearity of the system with \( V_3 \) equals to \( V_5 \) for different values of \( V_4 \). Experimental results an overall error of less than ± 0.5 % as compared to the theoretical ones. Output digital numbers shown in figures 6 and 7 are multiplied by a factor of 2 which may be adjusted in Eq. 19 to be, say, a multiple of 10.

**Conclusions**

The design of a flat-plate solar collector energy gain digital meter is introduced. Experimental results show an error of less than ± 0.5 %. the circuit accuracy is mainly affected by the DC offset of the integrators , the speed and the threshold voltage of the comparators, linearity of the VFC and the tolerance of the capacitive components used. However, higher accuracy is expected with carefully selected and adjusted components.
Figure (6) Experimental results of the solar collector gain meter showing its linearity

Figure (7) Experimental results of the flat solar collector gain digital meter

References