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Efficiency enhancement of stationary solar energy based power conversion systems in Canada

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ABSTRACT

This paper presents the optimum energy conversion conditions of stationary photovoltaic panels used for electrical power generation. The results are arrived at after performing calculations for 180 days in a given year at the latitude of St. John's, Newfoundland. The latitude of this city is close to other Canadian major population centers. Various angular orientations of sun's rays on the earth are considered. On a given day, the incident energy flux of sun is resolved into three components, and the conversion efficiency is based on the flux normal to the panels. The efficiency of conversion of the incident energy is measured with respect to a solar tracking process. The numbers of days in a given year are divided into two groups – one between the winter solstice and the spring equinox, and another between the spring equinox and the summer solstice.

The results show the existence of two maxima, one for each of the two periods. By setting the panels at each of these maxima, very significant improvement in energy conversion can be achieved.

1. Introduction

We are seeing high energy prices these days, and it is also being said that the days of low fuel costs are over. It is quite difficult to sustain the present day civilization when the cheap fuel is running out [1].

The combustion of fossil fuel causes global warming. We are witnessing the melting of the polar ice caps at rapid rates. The same is true for many glaciers which feed water to rivers. Major population centers of the world are located on the banks of these rivers.

If we continue to burn fossil fuels in the present manner, then it will bring about catastrophic events throughout the world.

Solar energy provides us with an alternative where there is no pollution of the environment and its use decreases the rate of depletion of energy reserves.

One uses the solar energy in converting this energy into (a) heat, and (b) electricity. In the first case, it is used for directly heating homes or for water heating where the sun's rays are incident on a panel containing circulating water in tubes. In the second case, it is used for generating electricity using photovoltaic panels.

In large number of cases, these panels are held stationary at an angle from the horizontal and, face south. In the present use this angle is not changed irrespective of seasons.

There have been different approaches to harness solar energy. In one approach [2–5], attempts have been made to enhance the energy conversion at the solar cell level by material scientists. The conversion efficiencies range between 12% and 15% of the incident energy.

In a solar tracking process, the solar panels are always oriented towards the sun's rays which are incident on them from the normal direction. The change in angle of the sun's rays is taken care of by the adjustments of two angles using electric motors. The two angles are adjusted in such a way that the sun's ray is always normal to the panels.

However, in the majority of cases, the panels are held stationary and at an arbitrary angle from the horizontal plane where they do not convert the energy to the maximum possible.

The objective of this work is to show how much more the efficiencies can be increased while the system remains simple (stationary panels). In this work the determination is made of optimum angles in each of the two periods which are between (a) the winter solstice and spring equinox, and (b) spring equinox and summer solstice.

It should be made clear here that in the stationary panels, one cannot avoid sun rays being incident in an oblique manner resulting in the decrease in efficiency. Since the angular spans of this incidence are different in the two periods (much wider in summer months as compared to winter months), it points to the existence of two separate optima.

The approach in this work is to orient the panel at each of the two separate optima.

The efficiencies for the stationary panels shown in this research are the upper bounds for oblique incidence cases. The results

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Nomenclature

$[R(Y1,\eta)]$	rotation matrix to transform incident solar energy vector
$\{I\}^1$	the intensity vector in $X1$–$Y1$–$Z1$ co-ordinate frame
$\{I\}^2$	the intensity vector in $X2$–$Y2$–$Z2$ co-ordinate frame
α	angle in vertical plane
α_s	angle in horizontal plane
γ	latitude of the place
δ	declination
$\theta 1$	angle of incidence
$\theta 2$	angle of refraction
h_s	hour angle at any instant of time
h_{sr}	hour angle at sunrise measured from noon
I_0	incident solar energy intensity of beam radiation
A	absorptance
r	reflectance
N	day number of a year
R	distance from the earth to sun
T	transmittance

Table 1
Latitudes of different cities.

Name of the place	Latitude (north)
Montreal, Quebec	45°30′
St. John's, Newfoundland	47°34′
Toronto, Ontario	43°40′
Vancouver, British Columbia	49°13′
Winnipeg, Manitoba	49°54′

clearly show – given the choice between tracking and stationary systems, one always obtains far higher efficiency in the tracking process.

Table 1 shows the latitudes of the main Canadian cities. It is clear from this table that all of these cities have latitudes within a narrow band. Since the orientation of the panels is dependent on latitude, it will be quite reasonable to study the energy conversion at one city, and use the results for others.

In this work, the city of St. John's has been selected with this objective in mind.

2. Theoretical considerations

Fig. 1 shows the sun's rays incident on a solar panel where the rays are incident at angles α_s and α in the horizontal and vertical planes, respectively. Suppose, the distance AC is equal to R then the components in the $X1$, and $Y1$ directions will be (refer to Fig. 2 for $X1$ and $Y1$ directions)

$$X_B = R\mathrm{COS}(\alpha_s)$$

or, by expressing the distance in a non dimensional manner, one can write

$$(X_B/R) = \mathrm{COS}(\alpha_s) \tag{1}$$

Similarly, one can write

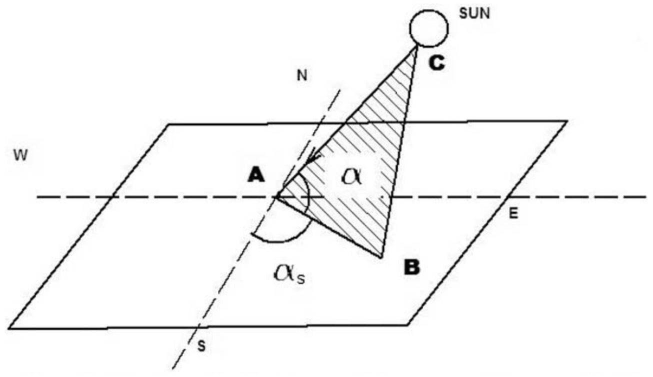

Fig. 1. Diagram showing the solar ray direction using two angles.

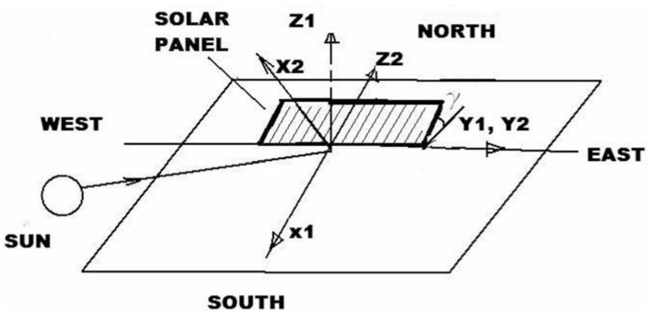

Fig. 2. Solar panel facing south and tilted at angle equal to latitude.

$$(Y_B/R) = \mathrm{SIN}(\alpha_s) \tag{2}$$

If the incident intensity of solar energy is I_0, then its three components in $X1$, $Y1$, and $Z1$ co-ordinates will be

$$I_{X1} = -I_0\cos(\alpha)\mathrm{COS}(\alpha_s) \tag{3}$$

$$I_{Y1} = -I_0\cos(\alpha)\mathrm{SIN}(\alpha_s) \tag{4}$$

$$I_{Z1} = -I_0\mathrm{SIN}(\alpha). \tag{5}$$

Let us represent the solar energy by a vector $\{I\}^1 = \{I_{X1}, I_{Y1}, I_{Z1}\}^\mathrm{T}$. In Fig. 2, one can express the vector $\{I\}^2$ in terms of $\{I\}^1$ in the matrix form as [6]

$$\underset{3\times1}{I^2} = \underset{3\times3}{[R(Y1,\eta)]}\ \underset{3\times1}{\{I\}^1} \tag{6}$$

In Fig. 2, the $X2$ direction is perpendicular to the panel, and the angle

$$\angle(X2 - O - X1) = \angle\eta = \angle(90 - \gamma) \tag{7}$$

Here, γ is the angle from the horizontal plane as shown in Fig. 2. In Eq. (6), $[R(Y1,\eta)]$ is the rotation matrix to transform the vector $\{I\}^1$ from $X1$–$Y1$–$Z1$ space to $X2$–$Y2$–$Z2$ space about the $Y1$ axis. A (3×3) transformation about $Y1$ axis by an angle η is given by [6]

$$[R(Y1,\eta)] = \begin{bmatrix} \cos\eta & 0 & \sin\eta \\ 0 & 1 & 0 \\ \sin\eta & 0 & \cos\eta \end{bmatrix} \tag{8}$$

It should be remembered that we are only interested in the negative component in the $X2$ direction i.e. I_{X2} should be negative. If this vector component is positive then there is no solar energy conversion by the panels due to the sun shining from behind the panels.

As far as the calculations of α_s and α are concerned, one can use the following formulas [7–9]

$$\delta = 23.45\sin\{(360/365)(284 + N)\} \tag{9}$$