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Tilt Angle Optimization for Maximum Solar Power Generation of a Solar Power Plant with Mirrors

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Abstract— **Solar power generation is mainly based on direct, diffused and reflected solar radiation. This paper will give an insight of the strategy of the implementation of optimization of the tilt angle of the solar panel to maximize the electricity generation, at presence of solar tracking mirrors. Mirrors will improve the reflected solar radiation, leading to increase the radiation on solar panel. For the purpose of analysis, as the site Toronto in Canada was selected. Renewable energy data was gathered through National Renewable Energy Laboratory (NREL). Energy increment due to the addition of mirrors is discussed and this will assist in taking appropriate measures for planning for the future.**

Keywords— Solar power, power generation optimization, tilt angle

I. Introduction

Power generation using solar energy, has been very popular in power industry, due to many advantages, like non-polluting nature, non-depletable, being a reliable and a free fuel

But still there exist few disadvantages associates with it. Solar energy highly depend uncontrollable factors such as latitude, season, time-of-day, and atmospheric conditions. And also it has a very low capacity factor [1], due to zero inertia; power generation might vary significantly depending on cloudiness

Most popular method of collecting solar energy are using solar photovoltaic and heating of a secondary fluid (solar thermal). Electricity generation using solar power will be reviewed here onward.

In order to maximize the energy conversion, solar radiation should land on photovoltaic cells in perpendicular manner. When the PV module is perpendicular to the sun, the power density of solar rays will always be at its maximum value.

Since earth is almost a sphere, solar rays will not land in perpendicular on every country, so solar panel has to be tilted. And again earth is rotating around its own axis, while rotating around the sun, so the tilt angle to get solar radiation to be perpendicular is always changing with the time. By properly installing a solar panel can enhance its application benefit because the amount of solar radiation incident upon the panel is mainly affected by the azimuth and tilt angles, but the tilt angle varies with factors such as the geographic latitude, climate condition and utilization period of time [2].

One option would be, installing solar tracking system to solar panels, where a tracker is a mechanical device that follows the direction of the sun. They are expensive, need significant amount of energy to drive a solar panel, which has a high amount of inertia [3]. Other option is to set the panel with a fixed optimum tilt angle (the angle can be changed in each month or each season manually, or have a one tilt angle for the whole year)

A. Effect from the reflected solar radiation

Generally a solar power plant has the effect from ground reflected solar radiation. Reflection coefficient of the ground may vary around 0.1 to 0.4 depending on the seasons and the country. This factor is called the albedo value[4].

When a country like Canada is considered, in summer season albedo value is low as 0.1, while in winter season, it can go up to 0.4, due to the fact that snow falls in winter season has a great capability of reflecting solar radiation[5].

A typical mirror has the albedo value close to 0.8, so if the mirrors were set up around the solar panel, amount of reflected solar radiation can be significantly improved.

II. Theory

A. Calculation of total solar radiation on tilted surface (HT)

All the radiation values are measured in MJ/m²/day. Incident total radiation on tilted surface can be defined as [6],

$$H_T = H_B + H_D + H_R$$

Where H_T, H_B, H_D and H_R are respectively daily total, beam, diffuse, and reflected radiation on a tilted surface in (MJ/m²/day).

1) Beam (Direct) Radiation Incident on a Tilted Surface (HB)

$$H_B = (H_g - H_d)R_b$$

Where Hg and Hd are respectively the average daily global and diffuse radiation on a horizontal surface in (MJ/m²/day). Rb is the ratio of the average daily beam radiation on a tilted surface to that on a horizontal surface.

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$$R_b = \frac{\cos(\emptyset - \beta)\cos(\delta)\sin(\omega) + \omega_{rad}\sin(\emptyset - \beta)\sin(\delta)}{\cos(\emptyset)\cos(\delta)\sin(\omega) + \omega_{rad}\sin(\emptyset)\sin(\delta)}$$

Where β, ϕ, δ and ω are the tilt angle, latitude of the site, declination angle(δ) and the hour angle (ω) respectively.

- Declination angle(δ)

$$\delta = 23.45\sin\left[360\left[\frac{284+n}{365}\right]\right]$$

Where n is number of days starting from 1st of January to the given date

- Hour angle (ω)

$$\omega = \cos^{-1}(-\tan(\delta)\tan(\emptyset - \beta)),$$
$$where\ sign(\delta) = sign(\emptyset)$$

$$\omega = \cos^{-1}(-\tan(\delta)\tan(\emptyset)),\ where\ sign(\delta) \neq sign(\emptyset)$$

Where, $\mathrm{sign}(x) = \frac{x}{|x|}$

2) Diffuse radiation incident on a Tilted Surface (HD)

$$H_D = R_d H_d$$

Rd is the ratio of the average daily diffuse radiation on a tilted surface, to that on a horizontal surface. It is determined based on the distribution of sky diffuse-radiation over the hemisphere. Assuming sky diffuse-radiation is to be isotropic Rd can be calculated with following formula,

$$R_d = \frac{(1+\cos(\beta))}{2}$$

3) Reflected radiation on a Tilted Surface (HR)

Reflected radiation without any reflectors around the solar panels,

$$H_{R,Grou\ nd} = H_g \rho \frac{(1-cos(\beta))}{2}$$

Where ρ is the solar reflectivity of ground,

Reflected radiation of the solar panel at presence of a mirror which has the configuration shown in Fig. 1.

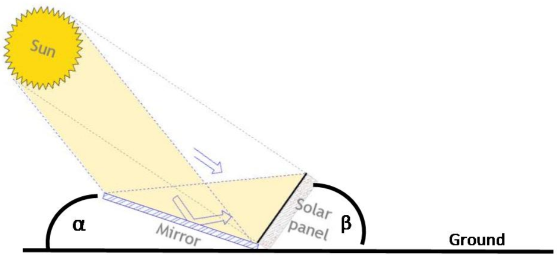

Fig 1 Configuration of the front mirror and solar panel

$$H_R = H_g \rho \frac{(1-cos(\beta))}{2} + H_g\, R_{d,miroor1} \rho_m \frac{(1-cos(\alpha+\beta))}{2}$$

Where ρ_m is the solar reflectivity of mirror and R_d, mirror1 is the ratio of radiation on tilted surface to a horizontal surface.

$$R_{d,mirror1} = \frac{(1+\cos(\alpha))}{2}$$

4) Objective function

Considering all the factors discussed above, objective function (Incident total radiation on tilted surface), can be written as,

- Without any reflectors,

$$H_{T,Ground} = (H_g - H_d)R_b + H_d\frac{(1+\cos(\beta))}{2} + H_g \rho \frac{(1-cos(\beta))}{2}$$

- With a mirror as a reflector (which is set up in front of the solar panel as shown in Fig. 1),

$$H_T = (H_g - H_d)R_b + H_d\frac{(1+\cos(\beta))}{2} + H_g \rho \frac{(1-cos(\beta))}{2} + H_g R_{d,miroor1}\rho_m \frac{(1-cos(\alpha+\beta))}{2}$$

III. Implementation

A. Configuration of the solar panel

To improve the electricity generation from a typical solar power plant, solar panel can be modified with addition of three mirrors to the solar panel as shown in Fig. 2 and Fig. 3.

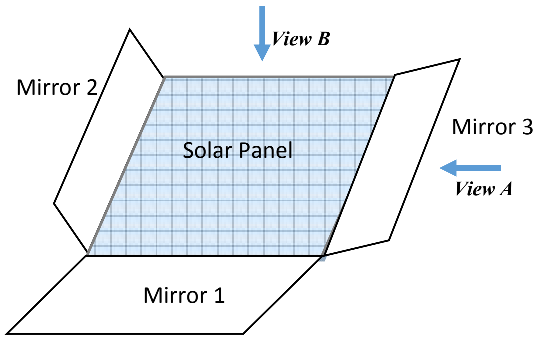

Fig. 2. Configuration of a single solar panel

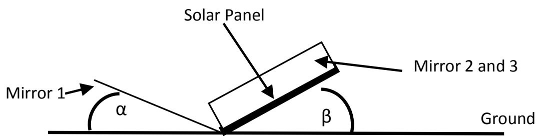

Fig. 3. Side view of a single solar panel (View A)

Fig. 4. Side view of a single solar panel (View B)

Arrangement, when looking at the cross section of the solar panel and, mirror 2 and 3, (disregarding the mirror 1), is shown in Fig. 4.

All the mirrors can track the movement of the sun as explained below,

- Mirror 1 will track the movement of sun seasonally (Movement from north to South)
- Mirror 2 and mirror 3 will track the movement of sun daily (movement from east to west)

B. Data Acquisition

In order to carry out the research study, Toronto in Canada was selected as the site.

National Renewable Energy Laboratory (NREL) established in Colorado, USA is a primary laboratory for renewable energy and energy efficiency research and development. They have published renewable energy data for many countries, obtained through satellites around the world. Using the software, System Advisor Model (SAM), provided by NREL, following data for Toronto were extracted,

- Solar irradiance data for a typical day in each month with an interval of an hour
- Average reflection coefficient (Albedo value) of ground for each month

C. Objective function

Using the modified configuration, new objective function can be written as,

Total irradiance (H_T)= beam irradiance + diffused irradiance + irradiance from ground reflection + irradiance from mirror 1 reflection + irradiance from mirror 2 and 3 reflection

$$H_T = (H_g - H_d)R_b + H_d\frac{(1+\cos(\beta))}{2} + H_g\rho\frac{(1-cos(\beta))}{2} + H_g R_{d,miroor1}\rho_m\frac{(1-cos(\alpha+\beta))}{2} + 2\times H_g R_b \rho_m \frac{(1-cos(\beta))}{2}$$

Subject to,

$$R_b = \frac{\cos(\emptyset-\beta)\cos(\delta)\sin(\omega)+\omega_{rad}\sin(\emptyset-\beta)\sin(\delta)}{\cos(\emptyset)\cos(\delta)\sin(\omega)+\omega_{rad}\sin(\emptyset)\sin(\delta)}$$

$$R_{d,mirror1} = \frac{(1+\cos(\alpha))}{2}$$

$where,\omega = \cos^{-1}(-\tan(\delta)\tan(\emptyset-\beta))$,
$where\ sign(\delta) = sign(\emptyset)$
$\omega = \cos^{-1}(-\tan(\delta)\tan(\emptyset))$, $where\ sign(\delta) \neq sign(\emptyset)$
And

$$\delta = 23.45\sin\left[360\left[\frac{284+n}{365}\right]\right]$$

∴ H_T, should be maximized for optimum tilt angle (β)

D. Optimization

All the calculations were done by using the software MATLAB R2015b.

Assumptions:

- Tilt angle of solar panel (β) = α and α is a constant throughout the year.
- For the purpose of calculating the declination angle, a typical day in every month falls on 15th day of the month (∴ n=15)

Energy for a day was calculated for a given tilt angle. This represents the energy of a typical day in a month. Since these given data are irradiance figures, calculated energy value would be a proportionate value to the actual energy value.

All tilt angles from 1° to 90° with a step of 1° were evaluated under the same method and calculated 90 points of energy values for a day.

One curve represents energy for a typical day with tilt angle variations from 1° to 90°.

This has been carried out for all 12 days, which represents 12 months of the year to obtain 12 curves.

Best fit quadratic equations were generated through MATLAB, which then used to calculate optimum tilt angle in each month

IV. RESULTS

A. Optimum tilt angle

Energy variation for different tilt angles of the solar panel, from 1° to 90° is shown in Fig. 5.

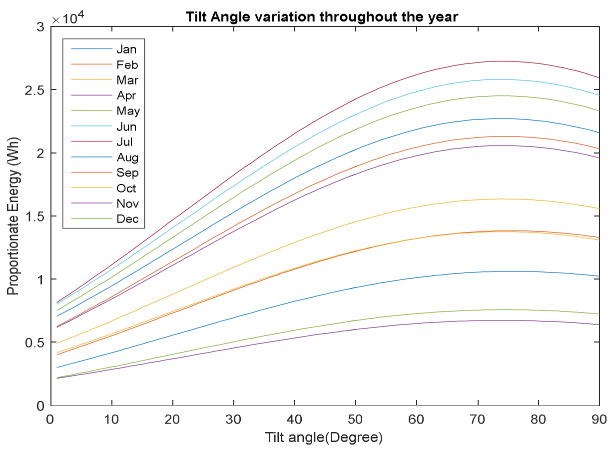

Fig. 5. Energy variation for different tilt angles of the solar panel (mirror 1 is fixed while mirror 2 and 3 track the movement of sun)

For each of the curve, following best fit quadratic equations were obtained, which has the format of ax^2+bx+c. parameter values for each month is shown in TABLE I.

Optimum tilt angle can be calculated through the derivation of the quadratic equation,

$$\therefore \text{Optimum tilt angle} = -2b/a$$

Calculated optimum tilt angle for each month s shown in TABLE II.

TABLE I. COEFFICIENTS OF BEST FIT QUADRATIC EQUATIONS FOR EACH MONTH

Month	a	b	c
January	-1.15	195.91	2311.02
February	-1.51	254.77	3100.98
March	-1.85	303.88	3808.97
April	-2.34	382.82	4800.95
May	-2.77	453.07	5866.93
June	-2.91	474.93	6278.25
July	-3.11	508.35	6320.17
August	-2.56	418.13	5508.07
September	-2.42	398.35	4831.29
October	-1.55	254.29	3254.63
November	-0.75	122.52	1682.67
December	-0.86	141.84	1698.37

TABLE II. OPTIMUM TILT ANGLE FOR EACH MONTH

Month	Jan	Feb	Mar	Apr	May
β_{Opt}	84.84	84.17	82.01	81.88	81.76

Month	Jun	July	Aug	Sept	Oct
β_{Opt}	81.67	81.80	81.69	82.25	82.05

Month	Nov	Dec
β_{Opt}	81.78	82.52

B. Increase in energy due to solar tracking mirrors

Optimum angles of the solar panel, without any mirror were also calculated along with the energy from the solar panel. Then incremental energy was calculated for each tilt angle for each month and results are shown in Fig. 6.

It can be observed that, percentage of incremental energy due to solar tracking mirrors is high around the optimum tilt angle of the solar panel.

V. CONCLUSIONS

While solar panel is fixed throughout the whole year, angle of mirrors will change due to solar tracking. Optimum angles and final arrangement of the mirrors for the case study of Toronto are as follows.

Solar panel

- Optimum tilt angle of solar panel without mirrors[7] ≈ 43.7°
- Optimum tilt angle of solar panel with three mirrors = 73°

Mirror 1

- Optimum tilt angle for mirror 1 will be changed in season wise, which means angle α is fixed throughout the day (It should be noted that, Mirror 1, was assumed to be fixed for the considered example)

Mirror 2 and 3

- These mirrors will track the sun daily and contribute to maximize electricity generation. So angles μ and γ will be changed constantly from tracking the sun

This analysis proved that, with an arrangement of solar tracking mirrors which was set up with solar panels, has an impact of 35% of energy increment in a solar power plant, established in Toronto, Canada.

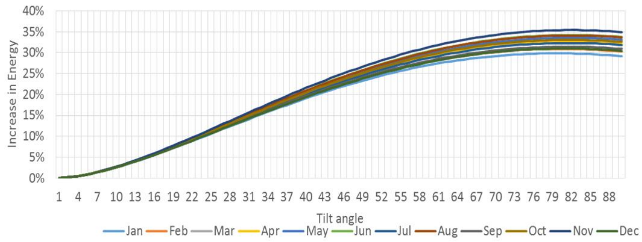

Figure 6 Energy increment due to reflection from mirrors in different tilt angles

Traditional way of using solar trackers to get more solar radiation is that, connecting solar trackers to solar panels. But according to this methodology, it is connected to mirrors, instead of solar panels. Since the weight of mirrors can be significantly less compared to solar panels, the energy requirement for the movement of mirror from solar tracking system is significantly low, due to low inertia. On the other side, installing mirrors take some space around the solar panel, so number of solar panels that can be installed in the premises will be limited. Therefore in this method, there are new positive and negative aspects to be considered.

But it should be noted that, percentage of energy increment, might vary with the location. While this research delivers a technical aspects of having a solar tracking mirrors, economic aspects has to be evaluated separately.

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