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ANALYSIS OF THE POWER GENERATION CAPABILITY OF A CURVED SOLAR ARRAY IN A VEHICULAR APPLICATION

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Abstract: This paper presents an analysis the power generated by the solar array of the Sikat 2 solar-powered vehicle designed to compete in the World Solar Challenge solar car race in Australia. The solar energy converted by a flat array depends on its orientation relative to the sun. The race presents a special challenge such that the array in the solar vehicle is generating power while it is travelling in a highway and its horizontal orientation continually changes with respect to the sun because of the varying road orientation. This is compounded by the fact that the sun is also changing position during each race day which spans early morning to late afternoon. The shape of the solar array surface also significantly affects the array power generated in relation to the sun position. Since the car is required to have low aerodynamic drag, the solar array surface is curved. Furthermore, there are appendages to the car that interacts with how the sun illuminates the panels and this results to occasions where shadowing is experienced by the array. Winning the race requires a strategy that relies heavily on information about the power generated by the array. The analysis was done through computer simulation. A computer program was written to estimate the power generated by the array involving the following: a) estimates of the solar irradiation at various race route positions and time of day; b) power generated by curved solar cells; c) effects of shadowing; d) various car velocity profiles; e) the string connection of the array. The results of the study indicates that cell mismatches due to the curvature and self-shadowing lead to significant reduction in power output compared to a same-size flat-profile array. The array characterization data can be used to define a race strategy to put the car in the best position to finish the race in the shortest time possible.

Key Words: solar array; solar cell; cell shading; solar car; solar irradiation

1. INTRODUCTION

Recently, interest in pure or hybrid electric vehicles (EVs) has risen, sparked by the rising cost of fossil fuels coupled with the development of allied technology particularly those related to batteries. The use of electric motors to drive the vehicle and batteries to power it is recognized as a cleaner approach than using internal combustion engines. However, it relies on electricity to charge its batteries. In the case of the Philippines, a large part of the total electricity available is produced by non-renewable means. A more ideal alternative is to use photovoltaic arrays to at least partially power the vehicle to reduce the consumption of fossil fuels.

Many people consider a vehicle solely or mostly powered by photovoltaic cells as currently impractical. This is due to the large amount of cells required to power the needs of conventional vehicular applications. However, there has been steady interest and participation in solar car racing since 1987. Two popular racing events are the World Solar Challenge in Australia and the North American Solar Challenge both having a cycle of two years. The goal of these events is to promote interest and development of solar technology for vehicular applications. To win the races, the participating teams must design the most efficient electric vehicle powered mostly by the energy obtained from the sun and finish the race course in the quickest time possible. In 2011, a team from De La Salle University built its third solar car named Sikat 2 designed to race in the World Solar Challenge.

Efficient solar racing vehicles minimize the aerodynamic drag which contributes to the energy losses when propelling the vehicle forward [Howlett,1997; Pudney,2002]. Reducing the drag invariably requires a curved design for the car body surfaces including those where the solar array is mounted on. The mounting of solar panels on a curved surface result to cell mismatches in terms of the amount of energy received by each cell since each one may be oriented to the sun differently. When the cells in a solar panel or strings of solar panels are electrically connected in series, the overall amount of energy obtained from the group is limited by the cell with the minimum amount of collected irradiation. This is explained by the action of each cell as a current generator whose output is proportional to the received solar energy. Since all cells are connected in series, the same amount of current must flow. When one or more cells receive less solar energy, the current output is limited by the cell(s) producing the least current [Vemuru, 2012] . Another source of cell mismatches is the shading of cells due to the blockage of direct sun rays on certain sections of the solar array by the driver’s canopy especially at low sun angles.

The amount of mismatches between differently oriented cells and the effects of canopy shading is dependent on the orientation of the cells and sun in relation to the car. Different positions of the sun lead to different amounts of mismatches. Since the car bearing varies with the road as the car travels along the race route and the sun position varies over the course of a racing day, the orientation of the sun relative to each cell continuously changes. All of these variations depend on how fast the car is travelling.

Apart from designing an efficient car, solar car teams must be able to predict the amount of energy that will be expended by the car to complete the course and the amount of energy that it can gather from the sun. The team needs to calculate the optimum velocity of their car to balance the expended and generated energies to finish the race with minimal amount of time.

This paper presents the results of an effort to develop a computational method to estimate the amount of energy that can be generated by the Sikat 2 solar car. Results can be used to develop an optimum race strategy or design for the solar array. Note, however, that the results are yet to be verified against the actual performance of the array as built in a future work. Since this work was only based on the 3D design model of the car, there can be discrepancies between the shape of the car represented by the model and the actual shape of the car (and solar array) as manufactured.

2. METHODOLOGY

Modeling the Solar Array

The shape of the top shell where the solar array is mounted on was modeled in 3D. A photo of the Sikat 2 solar array on the top shell is shown in Figure 1. Each of the solar cells was mapped on the grid derived from the 3D model (see Figure 2). A solar cell was treated as a tilted surface relative to the horizontal plane on the Earth's surface. Individual cells in the array are tilted differently because of the curvature of the array surface. Figure 3 illustrates how the sun is oriented relative to a surface tilted from the horizontal.

he amount of solar irradiation falling on the surface of a cell is expressed by

$$\mathbf{I_{global} = I_{direct} + I_{diffuse} + I_{reflected}} \qquad \textbf{(Eq. 1)}$$

where I_{global} is the total solar irradiation in Watt/meter^2. I_{direct} is the component that directly hits the surface, it is determined by

$$\mathbf{I_{direct} = I_{directHz} \cos \theta_N} \qquad \textbf{(Eq. 2)}$$

where $I_{directHz}$ is calculated using Bird and Hulstrom's solar irradiation model [Bird, 1981]. $I_{diffuse}$ is the component of radiation that is scattered in the atmosphere and is calculated using

$$\mathbf{I_{diffuse} = I_{diffuseHz} (1+\cos \theta_{NZ})/2} \qquad \textbf{(Eq. 3)}$$

where $I_{diffuseHz}$ is the diffuse radiation falling on a horizontal surface obtained using Bird and Hulstrom's model. $I_{reflected}$ is the radiation component that hits the ground and is reflected back onto the surface of the cell. It is given by

$$\mathbf{I_{reflected} = I_{globalHz} (1-\cos \theta_{NZ})/2} \qquad \textbf{(Eq. 4)}$$

where $I_{globalHz}$ is the Bird and Hulstrom's model total radiation onto a horizontal surface. The power generated by a cell was computed as

$$\mathbf{P_{cell} = I_{global} (\eta_{cell}) (A_{cell})} \qquad \textbf{(Eq. 5)}$$

where η_{cell} is the cell efficiency set at 21% and A_{cell} is the active area of the cell set at 0.015343542 square meter.

Figure 1. Sikat 2 solar array

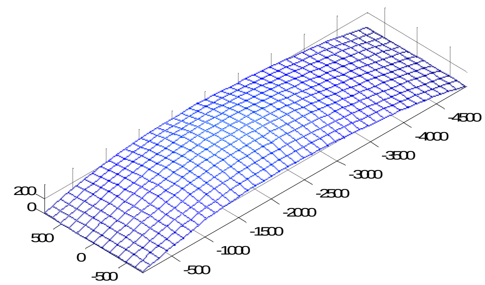
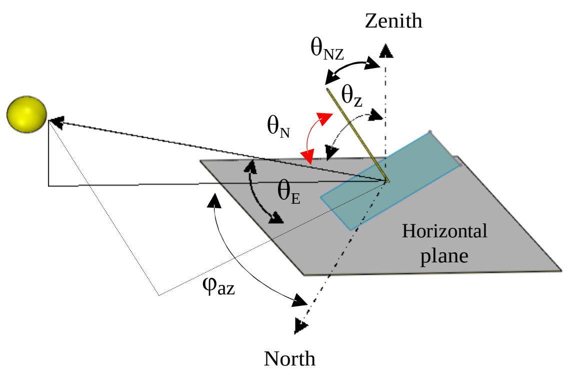


Figure 2. Cell grid



θ_N angle between the sun and normal to the surface
θ_E angle between the sun and surface
θ_Z angle between sun and the Zenith
φ_{az} solar azimuth angle

Figure 3

P_{cell} was calculated at regular intervals while the car is travelling towards the finish line using different reference speeds. The total energy collected by the array is the sum of the energy generated by all the cells over the entire duration of the race.

Effect of Cell Mismatches and Shading

The solar array is organized into three strings where each is connected to a maximum power point tracker (MPPT). The individual string power inputs to the MPPT are what matters in practice. However, to gain insight into how cell mismatches and shading limits the power generated, total energy was determined using individual cell, panel and string groupings.

Cells that are shaded or those oriented away from the direction of the sun produce the least power. The output power of a panel was determined by the product of the least power generated by any cell and the total number of cells. On the string grouping level, the total power was determined by the minimum power of the cell in the string multiplied by the total number of cells in the string.

The shading amount was approximated by geometric projections based on the portion of the driver's canopy illustrated in Figure 4. Partial shading was treated as a percentage of the area covered by the canopy shadow and the power output was proportionally adjusted at the cell level. A totally shadowed cell was assumed to receive only the diffuse and reflected components of the solar irradiation.

3. RESULTS AND DISCUSSION

Table 1 shows the total estimated energy collection for the entire race at 60, 70, 80 and 90 km/hour constant speeds. The figures in columns A, H and I indicate that in comparison with the total energy expected to be received by a flat array laid on a horizontal plane, the amount of total energy received by a curved array is significantly less. Assuming that the bypass diodes mounted on each of the strings do not turn on, the reduction can go down to 60% without the effects of shading and 48% with shading. The effect of mismatches of cells connected in series can be seen in columns D and F at the panel level, and D and H at the string level. The results of this analysis will help in redesigning the connection of panels into strings to minimize the effect of mismatches. As a reference, the expected energy collected due to the direct and diffuse irradiation on a horizontally oriented array are provided in columns B and C. The presence of the diffuse component and the reflected energy for the cells tilted at an angle from the horizontal plane is what prevents the received energy of the completely shadowed cells from dropping close to zero.

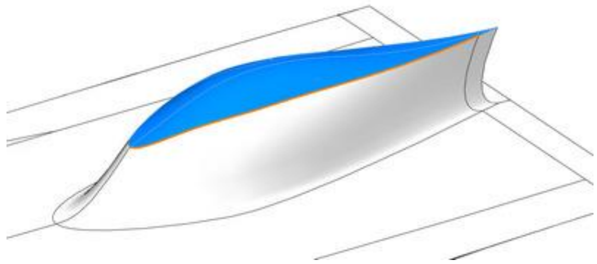


Figure 4. Canopy section used for shading analysis

Figure 5 illustrates the directionality associated with the reception of solar energy by the array. Here, the Sun is oriented 45^{o} to the right of the car from the driver's perspective and at an elevation of 20^{o}. It can be clearly seen that cells at the front-right corner will receive more energy than the ones close to the rear-left corner since the cells in the latter section are tilted more away from where the sun is. It becomes apparent that panels belonging to series-

Table . Total Estimated Energy Collection Under Various Conditions

	Total Estimated Energy Collection Under Various Conditions (Kilowatt-Hours) (see descriptions below)								
	A	B	C	D	E	F	G	H	I
Using constant 90 km/h	34.2	26.95	7.25	25.84	24.95	24.25	22.59	20.44	16.64
Using constant 80 km/h	37.5	29.44	8.06	29.94	28.87	28.15	26.03	23.8	19.1
Using constant 70 km/h	43.90	34.58	9.32	33.36	32.25	31.30	29.1	26.32	21.38
Using constant 60 km/h	50.81	39.97	10.83	39.26	38.02	36.86	4.92	31.01	24.95

A - Total global energy on a horizontal surface *with no shading*
B - Total direct energy on a horizontal surface *with no shading*
C - Total diffuse energy on a horizontal surface *with no shading*
D - Total global energy collected by the array *with no shading* and summed over individual cells
E - Total global energy collected by the array *with shading* and summed over individual cells
F - Total global energy collected by the array *with no shading* and summed over individual panels where each the energy of each cell in the panel is the minimum energy of mismatched cells

G - Total global energy collected by the array *with shading* and summed over individual panels where each the energy of each cell in the panel is the minimum energy of mismatched cells

H - Total global energy collected by the array *with no shading* and summed over individual strings where each the energy of each cell in the string is the minimum energy of mismatched cells

I - Total global energy collected by the array *with shading* and summed over individual strings where each the energy of each cell in the string is the minimum energy of mismatched cells

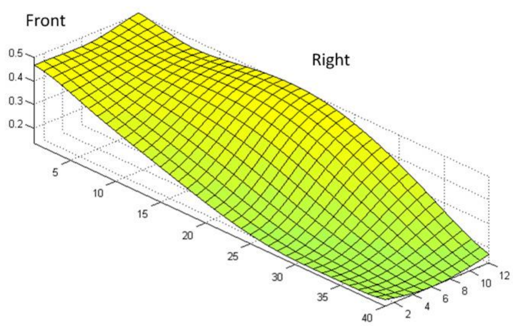


Figure 5. Relative strengths of the Irradiation of the Array Cells at 45^{o} orientation of the sun clockwise from the car front along the azimuth plane

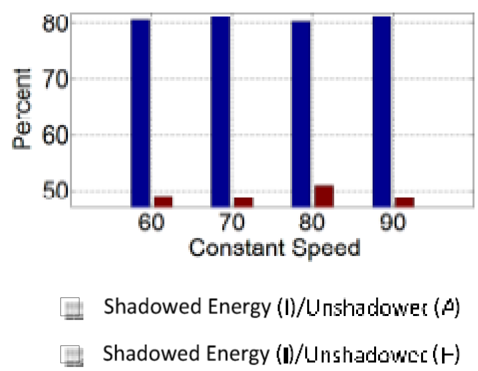


Figure 6. Ratios of Shadowed to Unshadowed Energy Collection at Various Speeds in km/h

connected strings must not be placed where a large variation in cell tilting exists. Otherwise large mismatches will occur and this will limit the power generation of the entire string.

Figure 6 shows how the ratio of the shadowed to unshadowed total received energy varies with the car speed. These variations can lead to a difference of ±15-30 minutes in the race finish time.

The analysis done on Sikat 2 can be applied to other electric-powered vehicular applications that make use of solar panels as a main or auxiliary power source. For example, electric commuter vehicles shuttling back and forth between terminals using fixed routes can benefit from a similar analysis. Many aspects of the vehicle design involving the placement and orientation of the panels can be specified to maximize the received solar energy. Alternately, routes can be chosen to maximize the same.

4. CONCLUSIONS

The power generation capability of the solar array of the DLSU-built solar car Sikat 2 during an entire race period of the World Solar Challenge was analyzed using computer simulation. The results show that the curved solar array generates significantly less power for the same irradiation as a horizontally laid flat array. While this expected in general, performance estimation specific to a particular solar array shape is required. The Sikat 2 array curvature introduces directionality to its performance. While the curvature cannot be eliminated particularly for solar race cars, information about the directional characteristics of its power generation allows optimal design of array strings and placement of cells or panels. Furthermore, the same information is needed when determining and executing optimal race strategies Future work can incorporate a more sophisticated modeling of the shading due to the driver's canopy.

5. REFERENCES

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