A SHADOW SENSOR FOR THE AVOIDANCE OF UNDESIRED CASTING OF SHADOWS FROM WIND ENERGY CONVERTERS ON APPOINTED OBJECTS

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ABSTRACT: In some cases the casting of shadows from the rotating blades of a Wind-Energy-Converter can cause problems for someone's living or working conditions because of the flickering daylight. Aim of this paper is to propose a possible shadow sensor, which would be able to detect the possibility of the casting of shadow. The results of experimental as well as theoretical investigations concerning a prototype will be presented. This sensor could be used for a control system, which avoids an overlap of the rotating shadow and a restricted area. A self-developed and investigated shadow sensor in tow variants, is presented with experimental and theoretical details.
Keywords: Control Systems, Visual Impact, Lighting

1 INTRODUCTION

Restrictive for the installation of a Wind-Energy Converter could be in some cases the possibility of temporary casting of shadows from the rotating blades on appointed objects. This effect can cause problems for someone's living or working conditions, because of the flickering daylight. Nowadays only a few single conflict-situations with this phenomenon are known. But in future, the expected increasing exploitation of wind energy with more and bigger Wind-Energy-Converter may lead to a shortage of remote locations, far from buildings. Basing on the authors contribution to the conference in Nice 1999 [4], more and further developed details especially concerning the detecting of possible shadowing with the help of a new sensor are presented.

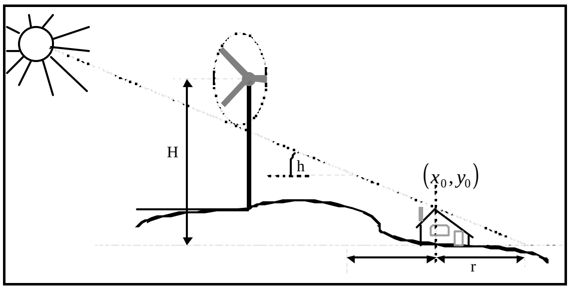

Figure 1: Casting of Shadows.

In recent different publications [1]...[4], the author has shown the possibility to build up a control-system, which enables us to avoid the casting of a rotating shadow on an appointed object. To reach this aim, the mathematical formulas describing the position of the sun relative to a Wind-Energy-Converter were combined with the projective mappings of the pole and rotator circle. With the help of the parameters like geographic position, month, day, time and the orientation of the blades the worked out formulas give the possibility to calculate the shadow region for every moment.

This information could be used by a control system to protect an appointed area from flickering daylight with minimum efficiency losses. Naturally, a measurement of the insolation ought to be done. Depending on this the control system has to be active or inactive.

This paper presents the self-developed shadow sensor based on two solar cells, whereby one of this is surmounted by a shadow frame in two different variants.

2 PHYSICAL FOUNDATIONS

To protect an appointed object from the shadow, imagine a circle around this, to define a restricted area. A criterion to determine the minimum radius, which is necessary to be sure that the shadows of the rotating blades will not cover the appointed object has already been worked out and presented in Nice [4].

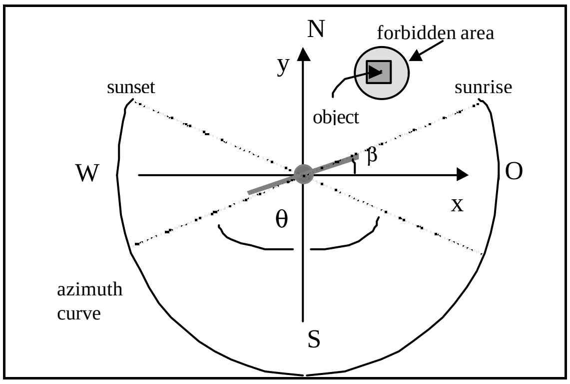

Figure 2: Appointed Object with 'forbidden circle'.

Similar to calculations of the solar insolation for Photovoltaic-Systems, it is possible to determine the time-dependent curvature of the shadow from the rotor circle in advance with sufficient precision. This includes also the dependence from the rotor angle relative to the east-west-axis [2].

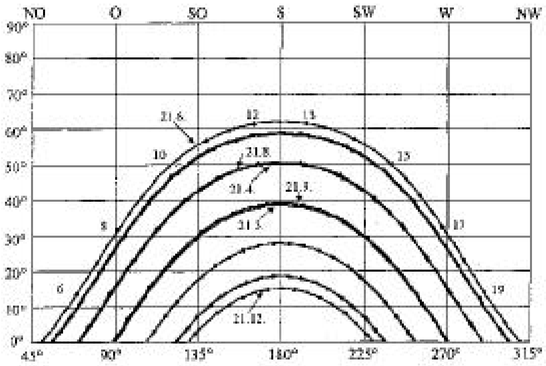

Figure 3: Sun's height at Hagen 51,5° N, 7,5° E.

The basic idea for the construction of a shadow sensor is to compare two identical solar cells, whereby one of them is equipped with a surmounting shadow frame. In cases of insolation with a shadow possibility, there would be a measurable difference concerning a suitable physical parameter.

For this purpose SUSE® solar cells where used. These commercial available cells are special manufactured for educational intentions, but with proofed quality.

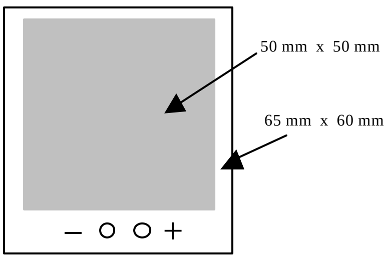

Figure 4: Dimensions of the SUSE® solar cells.

The following table shows the physical parameter of the used solar cells, at 1000 W/m², 25°C and AM=1,5.

Table I: Electrical data of the solar cells

Specification	Symbol + Unit	Min.	Standard	Max.
Maximum Power	P_{max} Watt(W)	0,40	0,42	
Optimum Voltage at MPP	U_{op} Volt(V)		0,500	
Optimum Current at MPP	I_{op} Ampere(A)	0,80	0,84	
Open Circuit Voltage	U_{oc} Watt(W)	<0,600	<0,618	<0,630
Closed Circuit Current	I_{sc} Watt(W)	0,89	0,94	
Efficiency	%	15,2	16,0	

The solar cells consist of mono crystalline silicon, mechanically stable mounted on a glass fibre plate covered with a transparent foil. In the case of a short cut, the occurring current I_{sc} is approximately equal to the photo induced current I_{ph}, depending on the insolation intensity as follows

$$I_K \approx I_{ph} = c_0 \cdot E \qquad (1)$$

$c_0 \triangleq$ photo current coefficient $\left[\frac{m^2}{V}\right]$

$E \triangleq$ insolation intensity $\left[\frac{W}{m^2}\right]$.

For an open circuit, the resulting voltage U_{sc} could be approximated as a linear function of $\ln(E)$

$$U_{oc} \propto \ln(E) \,. \qquad (2)$$

The figures 5 and 6 show the principal physical relation between voltage and current with the help of the characteristic curves with respect to the insolation intensity and temperature influence.

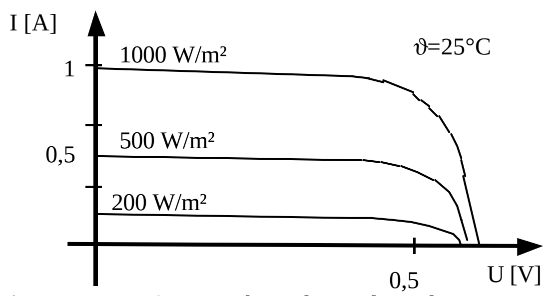

Figure 5: U-I-Curve with insolation dependency.

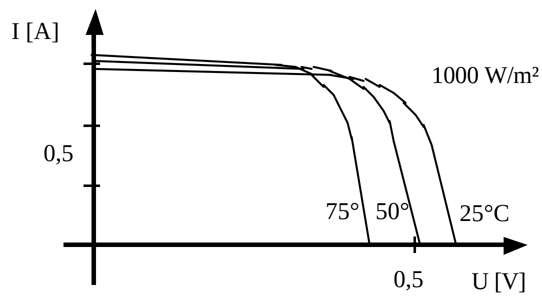

Figure 6: U-I-Curve with temperature influence.

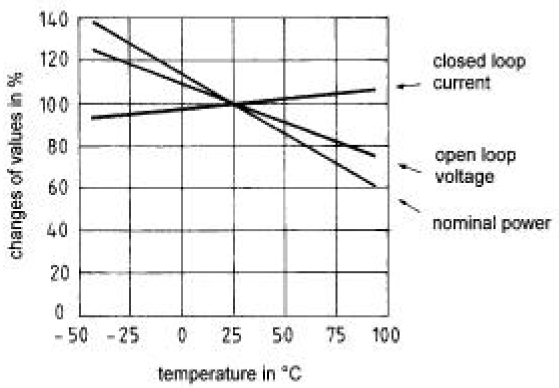

Figure 7: Temperature influence.

In order to get reproducible information from the shadow sensor, the temperature dependence has necessarily to be integrated in the electronic devise for compensating measurements. Figure 7 gives an impression of the temperature effect.

The total insolation on an area is called global insolation and can be divided into two parts with variable portions, the diffuse $E_{diffuse}$ and the directed insolation E_{direct}

$$E_{global} = E_{diffus} + E_{direct}\ , \quad \text{with} \tag{3}$$
$$E_{diffuse} = (1-l)\cdot E_{global}\ ,$$
$$E_{direct} = l\cdot E_{global}\ ,\ l\in[0,1]\ .$$

Most important for the possibility of shadow casting is the degree x of the directed insolation. It would be expected, that the 'sharpness' of the shadow is a function of this. The annual averaged value of l for the insolation conditions in Germany is nearly 0,4.

Because of the intention to measure the shadow of wind energy converter which would be seen by humans, it is obvious, to construct the sensor with principally respect to the subjective sensibility characteristic of the human eye. This characteristic is given by a function

$$y = a\cdot \ln(x) + b\ , \tag{4}$$

which is called "Weber-Fechners-Law" and is valid for the middle region of susceptibility to stimulus.

Regarding this relation, the voltage difference of the solar cells would be obviously a good physical parameter for the shadow measuring purpose, because of the similar behaviour.

3 SHADOW SENSOR

Two different kinds of sensors are presented, which differ in their sensibility and usage conditions. The advantages as well as disadvantages are discussed.

3.1 Sensor with 'Cross-Frame'

The first variant of the shadow sensor consist of two solar cells as described above. One of them is surmounted by three curved piece of metal as shown in figure 8.

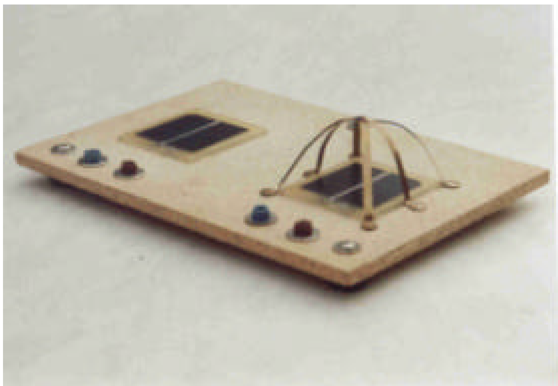

Figure 8: Experimental 'Cross-Frame' Sensor.

To approximate the expected value range for the voltage difference of the two solar cells regard the following expressions.

$$I = E\cdot A \ \hat{=}\ \text{insolation on the cell}\ [W]\ . \tag{5}$$

$$A = a^2 \ \hat{=}\ \text{cell surface}\ \left[m^2\right]. \tag{6}$$

The insolation of the reference cell equals I_0, whereas the insolation for the shadowed one could be approximated as:

$$I = I_{diffuse} + I_{direct}\ , \tag{7}$$

$$I_{diffuse} \approx (1-l)\cdot I_0\cdot\left(1-\frac{3\cdot p\cdot R\cdot \Delta s}{2\cdot p\cdot R^2}\right), \tag{8}$$

$$I_{direct} \approx k_1\cdot l\cdot I_0\cdot\left(1-\frac{2\cdot a\cdot\Delta s+\sqrt{2}\cdot a\cdot\Delta s}{a^2}\right), \tag{9}$$

with $k_1 \ \hat{=}$ correction factor, $\Delta s \ \hat{=}$ widths of the metal curves. Here it is assumed Δs to be small compared to a and the frame has the shape of a half bowl. The correction factor k_1 regards the angle of the directed insolation relative to the surface normal. In the case of rectangular insolation, the factor is maximum $k_1 = 1$.

With respect to formula (2) it can be shown that

$$\Delta U_{oc} \approx -c\cdot\ln\left[\begin{array}{l}(1-l)\cdot\left(1-\dfrac{3\cdot\Delta s}{\sqrt{2}\cdot a}\right)+\\ l\cdot k_2\cdot\left(1-\dfrac{\Delta s\cdot\left(2+\sqrt{2}\right)}{a}\right)\end{array}\right]. \tag{10}$$

The constant c is available form the data of U_{oc} for 1000 W/m², as listed in table I to be 0,6 V in the way

$$0{,}6 \approx c\cdot\ln(1000) \quad\Rightarrow\quad c\approx 0{,}0869\ \text{V}. \tag{11}$$

With $\Delta s = 0{,}35$ cm, $k_1 = 1$ and $l = 0$ to $l = 1$ the theoretical range of ΔU_{oc} for shadowing would be

$$\Delta U_{oc} \approx 14\ \text{mV to } 24\ \text{mV}. \tag{12}$$

This rough approximation confirms the principle possibility to give a threshold value for the existence of a shadow.

3.2 Sensor with 'Shadow-Wall'

The second variant of the shadow sensor is also equipped with a shadow frame, but in this case with a solid wall of white colour, as shown in figure 9.

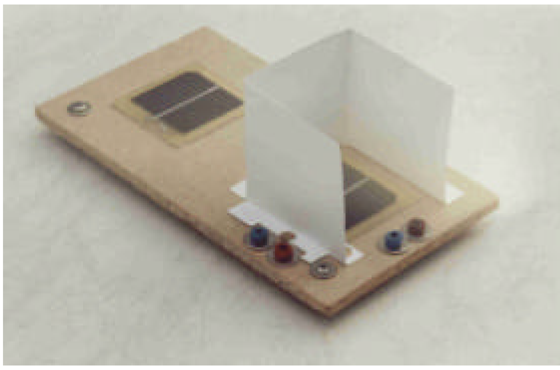

Figure 9: Experimental 'Shadow-Wall' Sensor.

To measure the shadow quality with this sensor, it is important to search an orientation relative to the sun, that the reference cell is free of shadow from the wall.

The position and dimension of the wall have been determined with respect to the sun's position as given in figure 3. If the sensor is horizontally oriented with the reference cell to the south, no direct insolation would be able to reach the shadowed cell.

Analogous to the approximation for the first variant one obtains

$$I_{diffuse} \approx (1-l)\cdot I_0 \cdot \left(1-\frac{1}{5}\right), \qquad (13)$$

$$I_{direct} \approx l \cdot I_0 \cdot \left(1-\frac{\Delta A}{a^2}\right), \qquad (14)$$

with $\Delta A \triangleq$ partial shadowed area.

The shadowing value of 1/5 would be approximately sufficient, with respect to the assumption, that the diffuse light from the other directions would be reflected by the white wall and guided to the solar cell.

If the sensor is directed to south as described above, formula (14) gives $I_{direct} = 0$ with $\Delta A = a^2$.

With respect to formula (2) it follows

$$\Delta U_{oc} \approx -c \cdot \ln\left[\begin{array}{l}(1-l)\cdot\left(1\ \frac{1}{5}\right)+\\ l\cdot\left(1-\frac{\Delta A}{a^2}\right)\end{array}\right] \qquad (15)$$

and $c \approx 0{,}0869$ V.

With $\Delta A = a^2$ and $l = 0$ to $l = 1$ the theoretical range of ΔU_{oc} for shadowing would be

$$\Delta U_{oc} \approx 19 \text{ mV to } \approx 600 \text{ mV}. \qquad (16)$$

As a consequence of these theoretical investigations, both concepts are in principle able to give a measure for the 'quality' of a shadow.

4 EXPERIMENTAL RESULTS

Both sensors were tested under real sunshine conditions. The insolation intensity was measured with the help of a Luxmeter. Here only the results concerning the open circuit voltages are presented. The measurements of the short cut currents are critical, because in cases shadowing with low insolation the values were too small and their difference is in-between the physical error range.

Table II shows some results of the first variant, when it is directly faced to the sun direction.

Table II: Results of the "Cross-Frame" Sensor

Shadow yes/no	**Lux ^ to sun**	**$U_{1,oc}$ [mV]**	**$U_{2,oc}$ [mV]**	**½DU$_{oc}$½ [mV]**
no	5980	526	523	3
no	4560	516	516	0
yes	7150	537	528	9
yes	116600	587	577	10
yes	107400	598	589	9
yes	102500	597	587	10
no	1920	516	514	2
no	1650	489	488	1
yes	72000	579	568	11

A disadvantage for general purposes is the necessity to face it directly to the sun to get reproducible values. On the other hand, more differentiated analysis of shadow qualities were in principle possible.

Variant two gives more significant results and a fixed positioning is possible, horizontal with the reference cell to the south. But more differentiated analysis of shadow qualities are difficult. Table III gives some results for this sensor.

Table III: Results of the "Shadow-Wall" Sensor

Shadow yes/no	**Lux ^ to sun**	**$U_{1,oc}$ [mV]**	**$U_{2,oc}$ [mV]**	**½DU$_{oc}$½ [mV]**
no	630	495	494	1
no	1700	515	514	1
yes	72000	595	566	29
yes	116600	567	530	37
yes	42000	572	552	20
yes	81000	589	568	21
no	1600	488	486	2

In summary the following threshold values indicate the casting of shadows,

„Cross-frame“ :	**if ½DU½ ≥ 9 mV**
„Shadow-wall“ :	**if ½DU½ ≥ 20 [mV]**

in a good agreement with the theoretical expected approximations. The cross-frame value is lower, because of half-shadowing effects.

5 CONCLUSION AND OUTLOOK

Both sensors are able to serve as shadow indicators for wind energy converter. The first could be mounted on the shaft, faced to the sun's position which could cause shadows on an appointed object. The second needs a separate shadow free place.

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