PRACTICAL REALISATION CONCEPT FOR A CONTROL SYSTEM 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 concept for a practical realisation of a control system, which avoids an overlap of the rotating shadow and a restricted area. Inherent for this concept is the possibility to calculate the time dependent shadow curvature in advance. The necessary software and hardware components are worked out and presented.
Keywords: Lighting; Control Systems; Numerical Methods

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 greater Wind-Energy-Converters may lead to a shortage of remote locations, far from buildings.

This work shows the possibility to build up a control-system, which enables us to avoid the casting of a rotating shadow on an appointed object. This option proposes a valuable tool to achieve more freedom in the choice of possible locations for Wind-Energy-Converters, and may be helpful to increase the general acceptance.

To reach this aim, the mathematical formulas describing the sun's position relative to a Wind-Energy-Converter were combined with the projective mappings of the pole and rotator circle. The worked out formulas enable us to calculate the time dependent shadow curvature in advance for every moment. Therefore the time intervals with an overlap of the rotating shadow and a restricted area could be predetermined.

These data can be stored in electronic devices and used by a μ-controller to realise a control-system to avoid the casting of rotating shadow with minimum efficiency losses.

This could be done with a worked out control-system-concept, which uses manipulations of the orientation of the rotor circle and causes a stop of the rotation only if it is really necessary.

2. PHYSICAL FOUNDATIONS

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 /1/.

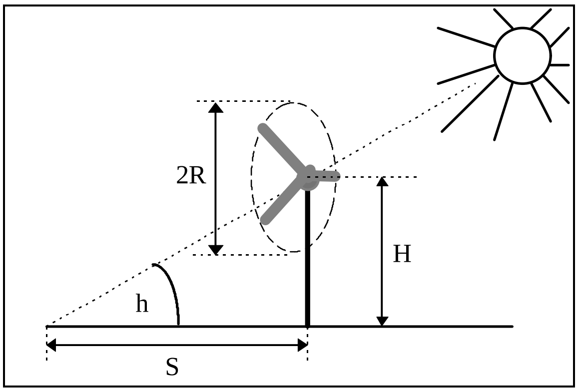

Figure 1: Sun's altitude and shadow

$$\left(S_x, S_y\right) = S(\sin\alpha, \cos\alpha)\,, \quad S = \frac{H}{\tan(h)} \qquad (1)$$

In this context, it is important to consider the pole height H relative to the ground of the appointed object.

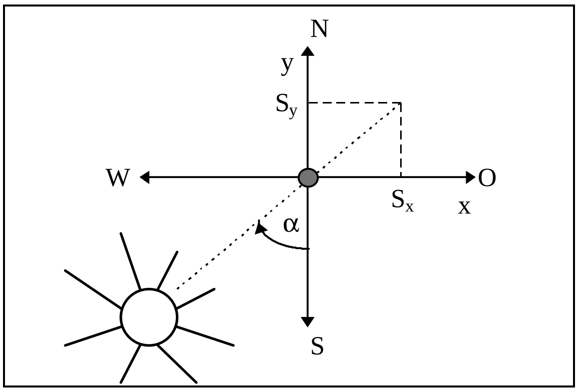

Figure 2: Sun's azimuth and coordinate system

This circumstance must not be neglected, especially for locations in hilly landscapes. Therefore the calculations are of local character for each affected object.

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 is worked out.

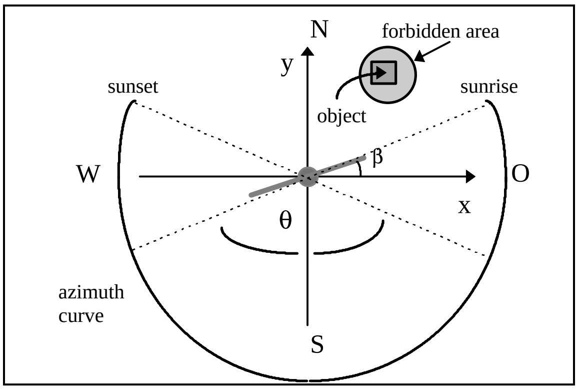

Figure 3: Appointed Object with 'forbidden circle'

With β as the angle between the plane of the rotor circle and the x-axis, which is equivalent to the deviation of its surface normal to the north, the coordinates of the circle curvature are determined by the following formula:

$$(x_R, y_R, z_R) = (0,0,H) + R \cdot \underline{\underline{D}}(\beta)(\cos t_R, 0, \sin t_R)^T \qquad (2)$$

with $t_R \in [0,2\pi]$ and

$\underline{\underline{D}}(\beta)$ the matrix of rotation relative to the z-axis :

$$\underline{\underline{D}}(\beta) = \begin{pmatrix} \cos\beta & -\sin\beta & 0 \\ \sin\beta & \cos\beta & 0 \\ 0 & 0 & 1 \end{pmatrix}.$$

To find the position of the rotor hub shadow use the transformation:

$$(0,0,H) \to \frac{H}{\tan(h)}(\sin\alpha, \cos\alpha) \quad , \quad \alpha \in [-\pi, \pi]. \qquad (3)$$

This coordinate could be everywhere in the area around the Wind-Energy-Converter except in the range of the daily angle θ as shown in Figure 3.

To determine the time dependent shadow region of the rotor circle in the ground-plane of the appointed object, the general transformation rule

$$\begin{aligned}(x, y, z) &= (x, y, 0) + (0, 0, z) \\ &\to (x, y) + \frac{z}{\tan(h)}(\sin\alpha, \cos\alpha)\end{aligned} \qquad (4)$$

leads to the result for the shadow-curvature:

$$\begin{aligned}(x_S, y_S) &= R(\cos t_R \cdot \cos\beta, \cos t_R \cdot \sin\beta) \\ &\quad + \frac{H + R\sin t_R}{\tan(h)}(\sin\alpha, \cos\alpha)\end{aligned} \qquad (5)$$

Whereas α and h are dependent from the calculable momentary sun's position /1/, the angle β depends on the wind direction and has therefore a stochastically character. But the necessary measurement of β is not difficult.

The next step is to give an expression for the 'forbidden circle'. With regard to the efficiency of the Wind-Energy-Converter, this circle has to be as small as possible. But with respect to the inhabitants of the object, there should be also enough tolerance-space around, because of the possible secondary disturbing light emissions from the shadowed surroundings.

The following proposal shows a possible practical method to define the restricted area. The coordinates of the 'forbidden circle' are determined as demonstrated in Figure 4 with :

$$(X, Y) = (x_0, y_0) + r \cdot (\cos t, \sin t) \ , \ t \in [0, 2\pi] \ , \qquad (6)$$

with centre (x_0, y_0) and radius r.

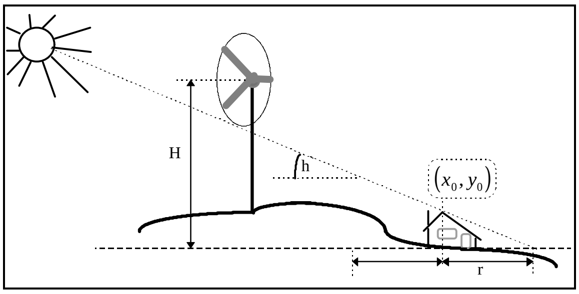

Figure 4: Geometric Correlation

To find a criterion to determine the minimum radius $r = r_{min}$ which is necessary, to be sure that the shadows of the rotating blades will not cover the object, we assume, that the sun, the rotor hub and the top of the object are all in one plane as shown in Figure 4. Then there exists a minimum sun altitude $h = h_r$, so that for angles $h > h_r$ the shadow of the rotator would possibly reach the object. If the altitude is deeper than h_r the shadow would reach a region behind the forbidden area, in this case it is therefore impossible for the wind-energy-converter to cast a shadow on the object. The altitude h_r is given by

$$\tan(h_r) = \frac{H - R - H_{object}}{\sqrt{x_0^2 + y_0^2}} = \frac{H_{object}}{r_{min}} \qquad (7)$$

and for r_{min} follows

$$r_{min} = \frac{H_{object}}{H - R - H_{object}} \cdot \sqrt{x_0^2 + y_0^2} \qquad (8)$$

with $\sqrt{x_0^2 + y_0^2} \equiv$ distance between wind-energy-converter and object.

With these formulas, it is possible to predetermine the times and conditions, when the shadows of the rotating blades will reach and overlap the 'forbidden area'.

Finally the formula for the determination of the shadow-overlap could be worked out as:

$$\boxed{\begin{aligned}&(x_S, y_S) = (X, Y)_{min} \Leftrightarrow \\ &R(\cos t_R \cdot \cos\beta, \cos t_R \cdot \sin\beta) \\ &\qquad + \frac{H + R\sin t_R}{\tan(h)}(\sin\alpha, \cos\alpha) \\ &\qquad = (x_0, y_0) + r_{min} \cdot (\cos(t), \sin(t))\end{aligned}}. \qquad (9)$$

3. CONTROL SYSTEM CONCEPT

The worked out interrelations give valuable information to build up a control system to avoid the shadowing with minimum efficiency losses /2/. The now calculable critical time intervals with possible shadow-overlap can be stored in electronic devices.

It is suitable to consider two extreme conditions concerning the angle β:

i) minimum Shadow Area $\Leftrightarrow$ Rotor Circle always *parallel* to Azimuth
ii) maximum Shadow Area $\Leftrightarrow$ Rotor Circle always *rectangular* to Azimuth

With the help of a computer program, it is possible to calculate the yearly time intervals for these cases in advance. These time intervals can be classified as follows:

Months-Intervals:

$M_{S,1} = [m_i, m_j]$ i<j with $i, j \in \{1..6\}$

for the first half-year and

$M_{S,2} = [m_i, m_j]$ i<j with $i, j \in \{6..12\}$

for the second half-year

Day-Intervals:

$D_S(\text{Month}) = [d_i, d_j]$ i<j ; $i, j \in \{1/.../28/,/29/,/30/,/31/\}$

according to the month

Time-Intervals:

i) $T_{S,1}(\text{day}) = [t_{\perp,in}, t_{\perp,out}]$ for maximum shadow

ii) $T_{S,2}(\text{day}) = [t_{||,in}, t_{||,out}]$ for minimum shadow

(with : $T_{S,2}(\text{day}) \subset T_{S,1}(\text{day})$)

The following information are inherent for the run of the control system:

- Date, Time
- Direct Insolation Intensity ($\rightarrow$ shadowing possible ?)
- Rotor-Angle β
- $\alpha_{lim,in}$ and $\alpha_{lim,out}$ Limit-Azimuth-Angles (in- and outgoing angle for the shadow through the tangent line from the Wind Energy Converter to the restricting circle around the object)

Based on this, Figure 5 shows the scheme of the worked out control system concept.

4. PRACTICAL REALISATION CONCEPT

The first step for a successful implementation of this control system is to determine the geographic position of the Wind-Energy-Converter and the geometrical correlation concerning a possibly affected object, as shown in Figure 4, including the limit angles $\alpha_{lim,in}$ and $\alpha_{lim,out}$.

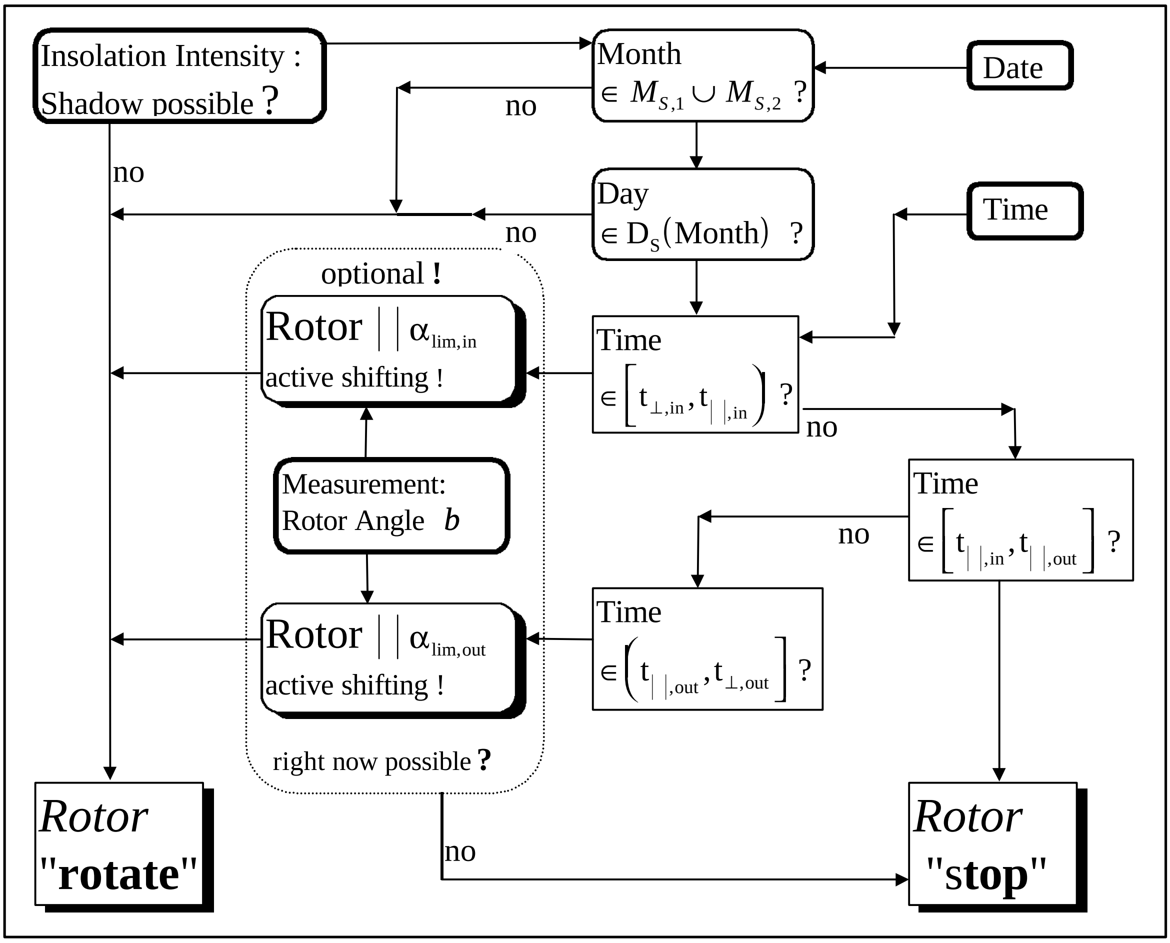

Figure 5: Scheme of the Control System

These tangential limit angles to the restricted circle relative to the Wind-Energy-Converter, as shown in Figure 6, can be calculated as follows:

$$\alpha_{lim,in} = \alpha_m - \Delta\alpha \quad ; \quad \alpha_{lim,out} = \alpha_m + \Delta\alpha \qquad (10)$$

with

$$\alpha_m = \arctan\left(\frac{y_0}{x_0}\right) \quad \text{and} \quad \Delta\alpha = \arcsin\left(\frac{r_{min}}{\sqrt{x_0^2 + y_0^2}}\right).$$

The time intervals with a possible shadow overlap can now be determined according to the sun's position /1/ via a computer program and stored.

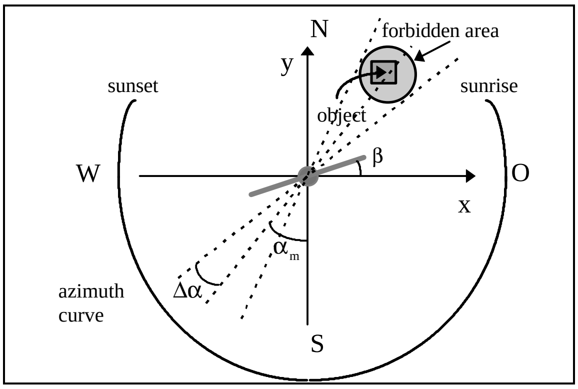

Figure 6: Limit-Azimuth-Angles

The next necessary information for the decisions of the control system according to Figure 5 are the date and time. This could be realised by an internal battery-buffered digital clock or with the help of a *Radio-Controlled Time*. The radio method is advantageous, because of its precision.

As it is not convenient to stop the rotation, if there is not enough sunshine to build an observable shadow, a measurement of the momentary insolation ought to be done.

The here presented proposal uses the two identical solar cells. One of the two cells should be surmounted with a shadow casting cross-frame as outlined in Figure 7.

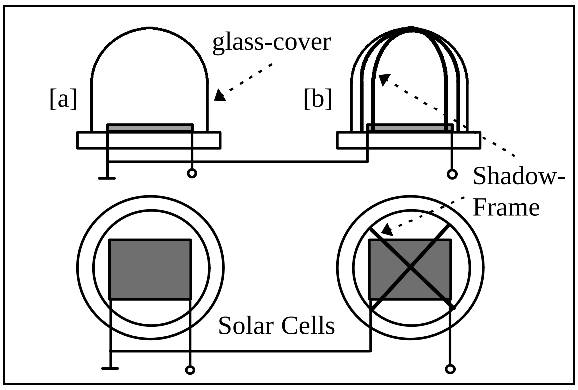

Figure 7: Shadow-Sensor

Sensor [a] gives a voltage, comparable to a reference voltage, which allows to indicate an existing insolation, whereas sensor [b] shows a significant difference to [a], only if there is a sufficient amount of direct insolation. Therefore, sensor [a] gives the information, that shadowing would be possible, and the voltage-difference between [a] and [b] is a measure of the shadow quality.

Dependent from the measurement of the shadow-sensor, the control program decides if the time check steps have to be activated.

In the case of detected shadow casting, the program searches for positive date and time overlaps with the stored intervals. If there is a coincidence, two possibilities are proposed. First, the rotor stops. Second, if the calculated maximum shadow would be able to overlap the 'forbidden circle', the rotor circle angle β could be shifted to $\alpha_{lim,in}$. When the minimum shadow reaches $\alpha_{lim,in}$, stop the rotor and shift the rotor angle β to $\alpha_{lim,out}$ and wait until the shadow reaches $\alpha_{lim,out}$, let the rotor rotate and give the angle β free, if the shadow time intervals are left.

The second method allows a further energy production with reduced efficiency. This option needs a measurement of the angle β. In summary, one obtains a control system, which avoids trouble with rotating shadows with minimum efficiency losses.

Figure 8 shows a possible scheme of the necessary hardware components.

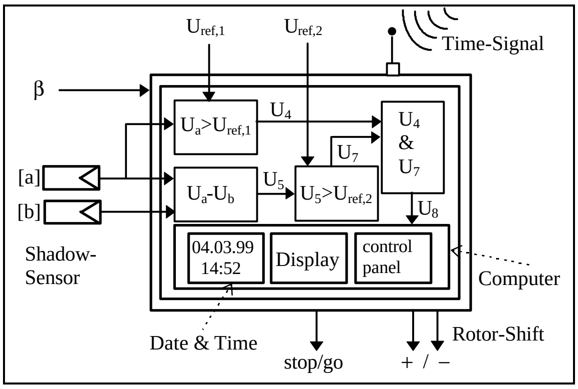

Figure 8: Electronic Device Scheme

5. CONCLUSION

A concept for the practical realisation of a control system to avoid temporary casting of shadows from a Wind-Energy-Converter causing trouble with flickering daylight is presented.

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