EXPECTED AND MEASURED VALUES OF LUMINANCE SENSORS IN DUAL-AXIS PHOTOVOLTAIC POSITIONING SYSTEM

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Abstract – A dual-axis photovoltaic positioning system has a primary task of directing a PV module towards the optimal light source when placed on electric vehicle. The idea of a positioning loop requires proper information on the PV module direction in order to get more irradiance, i.e. more energy. The assumption of a proper luminance sensor distribution is described in this paper. With this kind of distribution every angle position is described by a unique combination of luminance sensor readings. This paper compares expected readings and measured readings of a real model.

Keywords: cell systems, electric vehicles, energy system management

1. INTRODUCTION

When discussing electrical vehicles, the main issue is always storage of electrical energy. Battery development is one way of improving energy supply for the main drive of an electrical vehicle, while implementing some systems for storing alternative energy from surroundings can be another. In this paper the implementation of a PV module with a solar tracker will be discussed considering information needed for the tracking logic.

2. PV MODULE AND SOLLAR TRACKER DESCRIPTION

The PV module is represented by a square plane with the side length of a, which is mounted on the most exposed place for light from the environment – the roof of the electrical vehicle. While describing the PV module it will be assumed that it is fixated horizontally with the roof of the electrical vehicle. If the PV module is supposed to use a solar tracker, some direction adaptors must be installed in order to enable the PV module to always be able to track the optimal light source. All of those actions are justified only if they can gather some extra energy into the vehicle's battery, taking into consideration all the energy consumption of that kind of a solar tracker. Fixated holding point H is placed in the centre of the described PV plane, while the raising of the H above the roof plane will determine the angular twist of the PV module in all directions. Holding point H is also the centre of the 3-D space R3. Axes x and y are placed in the PV module plane, and axis z is placed vertically on that plane, also passing through H. When considering the length a and the distance between the sun and the PV module, we have to conclude that the distance is very large, has no effect on light strength, and all light beams are parallel on the whole PV module plane. Therefore, the distance parameter for describing R3 is no longer necessary, and only angles in (x, z) and (y, z) planes are enough to precisely describe the necessary direction of the PV module towards the sun, or towards the optimal light source. Placement of the holding points is shown in Fig. 1.

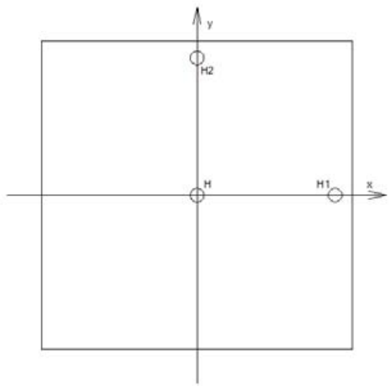

Fig. 1. Holding points distribution for the PV module

The battery used for power supply of the main drive of the electrical vehicle is also the main energy source for every electrical element in the vehicle. Therefore, it is also a power supply for the solar tracker system. The solar tracker system is useless if the gathered energy at the end of any given time period is smaller than the amount of energy that would be gathered into the battery through the fixated PV module (without the solar tracker). This happens if the solar tracker consumes more energy in its cycle than the PV module can store in the battery due to solar tracking. There are two main conditions for keeping the energy consumption of the solar tracker as minimal as possible. The first condition is to control the tracking cycles frequency well. If fast changes of input light angle are spotted, the tracking logic must recognize that it is inefficient to try to follow the input light, and assume that the change is generated by temporary movement oscillations which will probably disappear in a very short time. The other, energy oriented, condition is to determine if there is enough light for the PV module to produce electrical energy and store it in the battery for solar tracking to compensate its energy losses. In other words, if the PV module is moving in cloudy weather or in any kind of shadow, the tracking logic must stop itself from further solar tracking in order to reduce its own energy consumption to the minimum.

To be able to produce such solar tracker as described above, some information about illumination from the PV module environment must be collected into the brain of the solar tracking system. We have already concluded that the solar tracking system for electrical vehicles can work rather well by controlling only two angles of rotation of the PV module. Therefore, only two mechanical elements are sufficient for the PV module to track the light source. The main issue is how to gather as little information as possible about light in the environment (in order to reduce its energy consumption), but still get the accurate conclusion for the direction in which the PV module will increase electrical power input in the battery. If moving the free holding points H1 and H2 by two active mechanical elements is sufficient to include all of the PV module's directions in R3 space, then information from the environment must be separated in two groups, each assigned to one of those elements.

3. LUMINANCE SENSOR POSITIONING

The first group will not take into account influence of the other mechanical element which rotates the PV module through H and H1, therefore in the (x, y, z) plane. The simplest way to read the highest luminance is to place one illumination sensor on the PV module plane. Then by trying to move the PV module one can see whether the luminance is increasing or decreasing. The change of direction that increases the luminance of the sensor, therefore the PV module as well, must be applied as long as it can contribute to luminance enhancement. But this positioning model consumes too much energy, especially because it will very often go in the wrong direction before concluding that other direction is the right one. It does not even take into consideration that even the right direction movement is very expensive in the energy efficiency. But what if there were two of this kind of sensors, but oriented in different directions from each other? If one of those sensors was rotated towards the positive part of the x axis and the second one towards the negative part of the x axis, then the logical unit can compare those readings and conclude which direction of movement will increase luminance on the PV module. Those two sensors can be placed anywhere on the PV module plane, but their orientation must be in the (x, z) plane. In order to simplify the system, the sensors are placed on the x axis, by the edge of the PV module plane. Their coordinates in R3 are S1 (-a/2, 0, 0) and S2 (a/2, 0, 0). Rotation of both sensors is towards the positive part of the z axis. The rotation angles of both sensors are the same in order to achieve the symmetry of the readings, and also simplify the logical unit algorithm for solar tracking. Rotation angle of 30º is selected for this experiment, but any other can be used as well.

The luminance sensor has very useful characteristics for this application manifested in the way that input light beams change the sensor reading luminance as a cosine function of light input angle. In order to examine expectations of specific illuminations for the described system, it is supposed that the PV module is fixated in the (x, y) plane, while sensors luminance planes are rotated by 30º towards the positive part of the z axis.

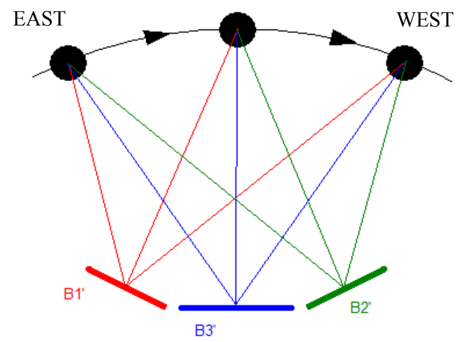

Fig. 2. Sensor distribution for H1 and H directional logic

If so, luminance of the PV module plane is defined by cosine function of input light angle limited in the span of [-90º, +90º], and is represented by characteristic *B3'* in the Fig 3. For the same reasons similar conclusions can be made for the illumination characteristics of luminance sensors. For example, the sensors *S1* luminance plane normal vector is angled 30º towards the positive part of *z* axis. If that luminance characteristic of the luminance sensor is a cosine function, it is easy to conclude that its luminance characteristic is a cosine function of input light angle limited in span of [-90º, +90º], moved by +30º. This characteristic is shown as *B1'* in Fig. 3. For the same reasons characteristics of the luminance sensor *S2* is a cosine function of input light angle limited in the span of [-90º, +90º], moved by -30º, and is shown as *B2'* in the picture Fig. 3.

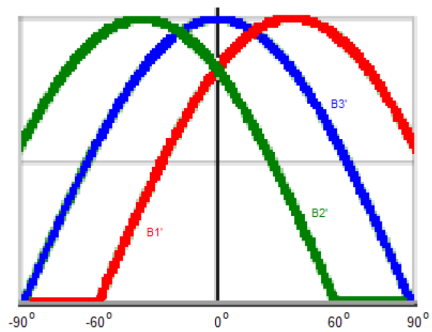

Fig. 3. Expected luminance characteristics of a dual-axis photovoltaic positioning system model

$$O_1' = O * \cos(\varphi - 30°) \quad (1)$$

$$O_2' = O * \cos(\varphi + 30°) \quad (2)$$

When examining characteristics in Fig. 3, two special characteristics of these expected readings can be seen. First of all, for every input light angle in the (x, z) plane there is a different combination of readings from S1 and S2. Therefore, every possible state of the PV module relative to the light source is described by a combination of readings from S1 and S2.

A similar logic can be used for holding points H2 and H, which would suggest that two more luminance sensors must be installed in the same way on the y axis as S1 and S2 were installed on the x axis. It would suggest that all the four luminance sensors are needed to describe three-dimensional space, which is also deprived of the distance r parameter. Nevertheless, the more sensors are installed in the tracking system, the more power consumption increases. But maybe one luminance sensor can be saved, because there are already two luminance sensors for H1. If mounted like S1 and S2, sensors S3 and S4 would have coordinates in R3 and as follows: S3 (0, -a/2, 0) and S4 (0, +a/2, 0). That would suggest that in direct orientation of the PV module towards the light source all four luminance sensors would read the same illumination. But in this moment two sensors already have the same readings (S1 and S2). Therefore, one sensor, say S4, can be saved for this directional loop. This extraction of one luminance sensor introduces some asymmetrical elements into readings characteristics, but nothing essential is changed, except that arithmetical mean value of S1 and S2 readings is used instead of S4 reading.

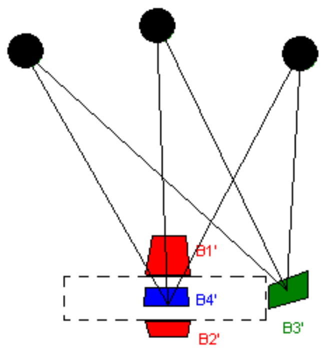

Fig. 4. Sensor distribution for *H2* and *H1* directional logic

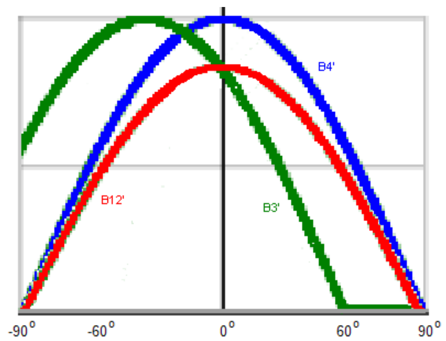

Fig. 5. Expected luminance characteristics of a dual-axis photovoltaic positioning system model

$$O_{12}' = O * \cos 30° * \cos\varphi \qquad (3)$$

$$O_3' = O * \cos 30° * \cos(\varphi + 30°) \qquad (4)$$

If one could prove that expected luminance characteristics are correct, the solar tracker system would be proven as viable. Then the only questions left for studying would be how to control this tracker so that it can gather enough extra power into the battery after tracker's energy consumption is taken into consideration. In the follow-up real time measurement is presented, which will try to prove all expected results described so far.

4. LUMINANCE CHARACTERISTICS MEASUREMENT

The real mechanical model that was used to acquire data for this measurement is shown in Fig. 6 and all data was automatically stored in Microsoft Office Excel Sheet by visualization software of a PLC device which is used to gather all readings into one digital database. The visualization application is shown in Fig. 7.

Fig. 6. A mechanical model for positioning the angle with *H1* and *H2*

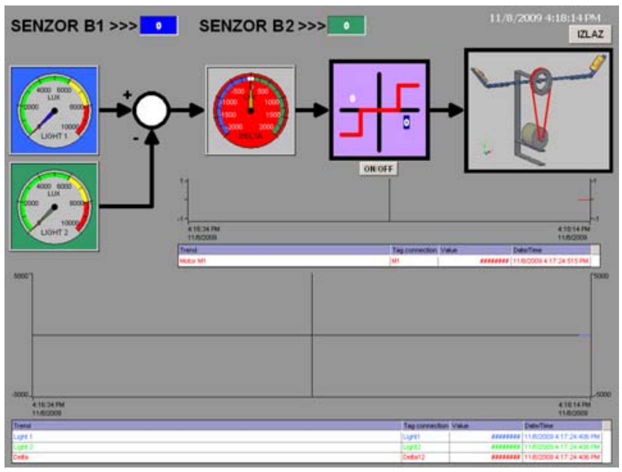

Fig. 7. Visualization application for data acquisition

A mechanical model is made to generate conditions as expected in real application of the dual-axis photovoltaic positioning system. Luminance sensors are placed close to each other unlike the light source which can be very far. Sensor readings are measured for various angles of the PV module surface. Theoretical values are represented in Fig 3, but mechanical limitations will narrow the range of readings to [-55°, +55°].

Measured results are presented in Table 1.

TABLE I. Measured values of luminance sensors O1' and O2'

	ANGLE α / °	O_1' / lux	O_2' / lux
1.	-55	188,8	94,4
2.	-48	201,6	137,6
3.	-40	209,6	158,4
4.	-33	219,2	177,6
5.	-26	228,8	198,4
6.	-18	232,0	209,6
7.	-11	233,6	219,2
8.	-4	233,6	227,2
9.	4	225,6	232,0
10.	11	217,6	232,0
11.	18	203,2	227,2
12.	26	187,2	220,8
13.	33	155,2	203,2
14.	40	123,2	188,8
15.	48	86,4	176,0
16.	55	68,8	171,2

When values from Table 1 are graphically presented, it can be seen that luminance diagrams are very similar to the ones expected and shown in Fig 3.

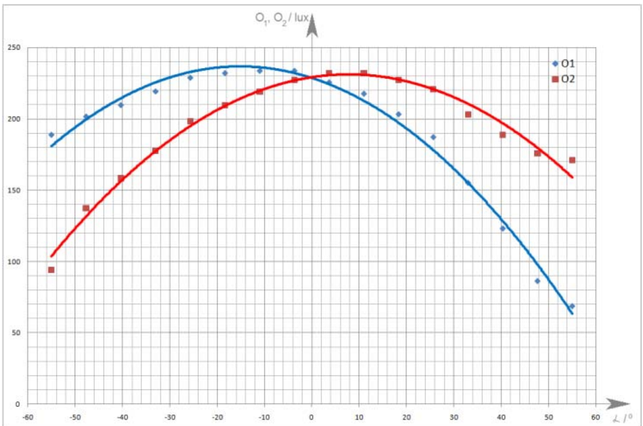

Fig. 8. Measured values of O_1' and O_2' with trend approximation

Approximated trend lines of luminance sensor readings generated by Microsoft Excel are as follows:

$$O_1' = 235\cos(\varphi + 15°) \quad (5)$$
$$O_2' = 235 * \cos(\varphi - 15°) \quad (6)$$

It is necessary to point out that Fig. 8 shows raw data gathered from the luminance sensors analogue outputs. When observed in general, characteristics in Fig. 8 are very near to the ones in Fig. 3, as expected in the theoretical model. However, some differences emerge, but they can be explained by environmental conditions that were present during the measurement. The first condition was shown in the voltage difference between sensors B_2' and B_1'. This voltage difference was 20 mV per 5 V. This error can be easily corrected in the positioning procedure, but it is unique for each copy of this system. The second condition was that the measurement was conducted only in the (x, y) plane, but the light source had input angle $\varphi \neq 0$. Therefore, asymmetry emerges in characteristics for the negative and the positive span of angle values. Finally, the third condition was the Plexiglas caps on luminance sensors, above the photodiode. They were placed on sensors to additionally direct light beams vertically on the photodiodes. They influence the characteristics in the way that the top of the cosine function is extended through a short span of input angles around 0°.

When all conditions are taken into consideration, it can be concluded that measured characteristics confirm our expectations in every way. With some modifications, considering the listed reasons for aberration from the ideal characteristics, the new positioning system idea proved to be worthwhile in terms of energy management and savings.

5. CONCLUSION

Results of the performed measurements on luminance sensors B1' and B2' for the positioning loop of the first directional loop (H1 and H) show that all assumptions were justified. They also confirm correct approach to the positioning loop idea as appropriate for the described application. This confirmation is a foundation for justifying the dual-axis positioning solar system. Relative energy gain in real operating conditions depends on how well exceptions are taken into consideration while moving the electric car in 3-D space to reduce inefficient energy loss and the fact that even when the electric car stops running, the energy from the PV module is still collected in the battery. It is of the greatest importance to direct the PV module in the best direction to gather as much energy as possible. If it is successful, energy gain can reach even a few percent of the total power consumption of the electric car. The PV module and the positioning system will be installed on the roof of the electric car, since it is the most appropriate place for collecting solar power from vehicle surroundings. The electric car is run by a DC motor, so the DC power is already available, and a logical circuit is implemented into the electric car logical unit, so that additional energy losses are reduced to a minimum.

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