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Sun trajectory modeling for specific location using PV measured data

Abstract*. In order to research the PV module characterization it was necessary to develop the Prototype PV characterization station. Among other possibilities derived from the measured results of Prototype PV characterization station it is also possible to model the Sun trajectory at installation location. Such measured results can be used to model Sun trajectory. Also, the Sun trajectory generated using presented model is verified with conventional analytical model Sun trajectory. Some conclusions for new approach are presented and discussed.*

Streszczenie. *Przy charakteryzacji prototypu stacji fotowoltaicznej zalecane jest modelowanie trajektorioi słońca. Przedstawiono taki model wykonany na podstawie badań eksperymentalnych.* ***Modelowanie trajektorii słońca w określonej lokalizacji na podstawie eksperymentu***

Keywords: analytical models, power system measurement, photovoltaic cells, Sun trajectory.
Słowa kluczowe: modelowanie trajektorii słońca, stacja fotowoltaiczna

Introduction

When number of PV plants reach certain installed electrical production power it is common for the price of energy to drop. In such cases it is necessary to improve the efficiency of electrical energy production. The simplest way to improve such energy production is upgrading from the fixed PV system to single-axis or dual-axis tracking system, as described in [1, 2, 3]. When using single or dual-axis tracking system it is necessary to know Sun trajectory in order for control system to follow it during the day, as described in [4]. The main goal of this research is to show that measured results provided by prototype PV characterization station, described in detail in [5], can be used to describe Sun trajectory.

The prototype PV characterization station is used for collecting the data significant for PV plant electrical energy production. These measured results, gained from prototype PV characterization station, and electrical energy production modeling results, gained as described in [6], can be used to provide the azimuth and slope values of real trajectory for the Sun in installation location. Also, these results can be used to provide some optimization results, for example the fixed optimum slope, as described in [7]. The results of this model should correspond to conventional analytical model results as described in [8].

Prototype PV characterization station

The prototype PV characterization station, presented in Fig. 1, was designed as a basis for PV energy characterization analysis. Station is developed to enable advanced and more precise determination of realistic performance for PV system with different technologies and configurations at specific location. Measured data allow full assessment of electrical energy production for one-axis system, dual-axis system and fixed alignment under different azimuths and inclination angles for several PV technologies. The station consists of three PV modules (with monocrystalline, polycrystalline and amorphous technologies) mounted on the two axes rotator, central control, measuring and data storing unit (with network communication). This characterization station is installed on the roof of the University building in Zagreb. The data storing unit is installed indoor with web based access. Control unit and data storing unit are integrated in Ethernet LAN using Beckhoff Automation Ethernet TCP/IP, which is detail described in [5]. The measured results are representative for Croatia, but can be generalized for wider area, as described in [9].

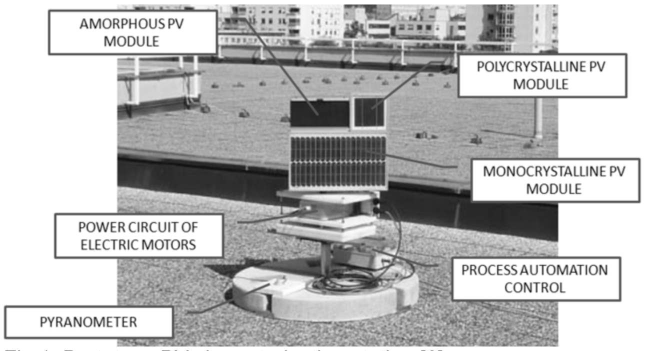

Fig.1. Prototype PV characterization station [6]

Table 1. PV modules nominal data

	Poly-crystalline	Amorphous	Mono-crystalline
Short circuit current / A	8.71	0.165	1.36
Open circuit voltage / V	0.63	22.5	20.5
Power in MPP / W	3.47	2.0	20.0
Current in MPP / A	7.70	0.138	1.21
Voltage in MPP / V	0.45	14.5	16.5

The nominal data for three PV panels used in this research are provided in the Table 1. Since all PV modules have low nominal output power it can be expected that measuring error will have significant impact on results of this research. Therefore, the highest power PV module with monocrystalline technology was used where only one technology is needed. In the future this characterization station will be scaled in order to use much bigger panels.

All measurements, electrical and nonelectrical, are stored into the database. The measured data stored in are as follows: the measuring reference number, time noted for each date as “hh:mm:ss”, insolation H, orientation of the PV module as azimuth angle Xd (0°-180°, east-west) and inclination angle Yd (0°-90°, vertical-horizontal), open-circuit voltage U_{ph}, (while the current and power are equal to 0), the short-circuit current I_{ks} (while voltage and power are equal to 0) and one PV module operating point (with constant load) by voltage U, current I and power P. The sample of the database for monocrystalline PV module is presented in the Table 2.

Table 2. PV module measurement database sample

Row	Time	H / W/m²	Xd / °	Yd / °	Uph / mV	Iks / mA	U / mV	I / mA	P / mW
474	12:50:31	44.744	178	90	17.200	150	4.300	155	2.079
475	12:50:36	44.948	173	90	18.100	280	5.700	295	667
476	12:50:41	44.868	164	90	18.600	395	11.500	335	1.682
477	12:50:46	44.888	155	90	19.000	510	13.700	415	3.853
478	12:50:51	44.756	146	90	19.200	600	14.900	510	5.686
479	12:50:56	44.804	137	90	19.400	685	15.700	535	7.599
480	12:51:01	44.996	128	90	19.500	750	16.100	545	8.400
481	12:51:06	44.900	119	90	19.600	795	16.300	555	8.775
482	12:51:11	44.952	110	90	19.700	825	16.400	560	9.047
483	12:51:16	44.860	101	90	19.700	835	16.400	560	9.184
484	12:51:21	44.904	92	90	19.600	825	16.400	560	9.184
485	12:51:26	45.008	83	90	19.600	790	16.200	550	9.184
486	12:51:31	44.968	74	90	19.400	740	15.900	545	8.910
487	12:51:36	44.880	65	90	19.300	670	15.500	530	8.666
488	12:51:41	44.916	56	90	19.100	585	14.700	505	8.215
489	12:51:46	44.896	47	90	18.800	475	13.100	450	7.424
490	12:51:51	44.792	38	90	18.400	360	10.200	360	5.895

When these data are used and processed by analytical model described in [6] they can provide the various useful results for modeling the PV module (e.g., maximal power point determination MPP). The modeling results are illustrated in the Table 3: PV module dark current I_0, temperature equivalent voltage U_t, MPP operating point voltage U_m, current I_m, and power P_m, modeled temperature of PV cells T_{sp}, and finaly equivalent modeled resistance R'_s.

Table 3. PV module analysis database sample

Row	Io / A	Ut / mV	Um / V	Im / mA	Pm / W	Tsp / °	Rs / °C
476	1E-252	32,11	10,29	389	4,00	13,25	21,00
477	3E-252	32,84	12,42	507	6,30	19,75	12,64
478	4E-252	33,20	14,04	598	8,40	22,95	8,31
479	6E-252	33,56	14,55	683	9,93	26,15	6,82
480	8E-252	33,74	14,71	747	10,99	27,75	6,16
481	9E-252	33,92	14,76	792	11,69	29,35	5,87
482	1E-251	34,10	14,72	822	12,10	30,95	5,82
483	1E-251	34,10	14,66	832	12,20	30,95	5,82
484	9E-252	33,92	14,77	822	12,14	29,35	5,64
485	9E-252	33,92	14,60	787	11,49	29,35	6,10
486	6E-252	33,55	14,54	737	10,72	26,05	6,33
487	5E-252	33,37	14,38	668	9,61	24,45	7,06
488	3E-252	33,01	13,91	583	8,11	21,25	8,57
489	2E-252	32,47	12,73	473	6,02	16,45	12,45
490	8E-253	31,75	28,38	359	10,19	10,05	-28,33

Fig.2. Prototype PV characterization station [6]

Considering the view of true South from the prototype PV characterization station it can be expected that conventionally modelled results and modelled results from measured data will have rather high difference in morning and evening due to obstacles placed in East and West. Fig. 2 presents horizon for true South view of prototype PV characterization station.

Modelling of Sun trajectory

The conventional modeling of Sun trajectory is generally developed from location on Earth surface and the time (date, hour and minute). These methods also include some deviations from ideal trajectory such as *civil time* to include time zones, summer and winter time (±1 hour), etc. One of these methods is described in [10], and is used in this research. Described model is also used in common analytical software as presented in [11].

For any location with the latitude φ, Sun hour ω and declination δ one can provide the mathematical position of Sun's center in the sky. This position is described using angles of azimuth and height. The Sun hour ω is the angular value of time which refers to solar noon rather than civil noon for any given location. The declination δ is angle between incoming Sun irradiation and horizontal surface defined by the Equator. Sun's height γ_s is the angle determined by the horizontal plane in the specific location and the line between Sun's center and the location. It can be calculated from the equation (1) as provided in [10].

$$\gamma_s = \sin^{-1}\begin{pmatrix} \sin\varphi \cdot \sin\delta \\ + \cos\varphi \cdot \cos\delta \cdot \cos\omega \end{pmatrix} \tag{1}$$

Sun's azimuth α_s is angle between South, where supposed as 0°, and described with negative values towards north across east to -180° and across west in positive values +180°. It can be calculated from the equations (2) and (3) as provided in [10].

$$\cos\alpha_s = \frac{\sin\varphi \cdot \sin\gamma_s - \sin\delta}{\cos\varphi \cdot \cos\gamma_s} \tag{2}$$

$$\sin\alpha_s = \frac{\cos\delta \cdot \sin\omega}{\cos\gamma_s} \tag{3}$$

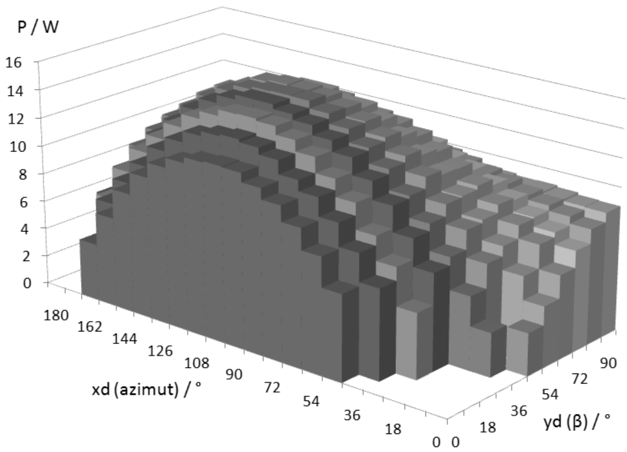

Fig.3. Example of MPP power data (4. 10. 2009., 12:00)

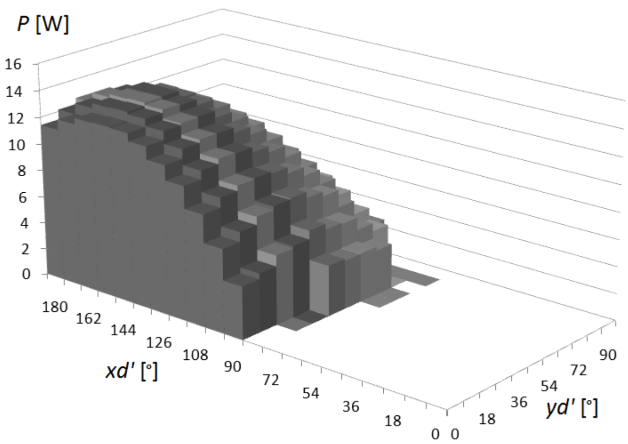

Fig.4. Example of MPP power data (4. 10. 2009., 17:00)

The values of Sun height γ_s and azimuth α_s are the conventional modeling results used in this research. The results for azimuth are provided as: -90° for East, 0° for South and +90° for West. The results for slope are provided as: 0° for Sun on the Horizon (vertical surface of PV module is optimal) and +90° for Sun vertical to location (horizontal surface of PV module is optimal).

For the prototype PV characterization station results available in database described in previous section one can filter the result of power for MPP operating point with associated azimuth and slope. One complete cycle can be extracted, as presented in Fig. 3 and Fig. 4. In this extraction the Sun position can be expected to coincide with the highest PV module MPP power. If such assumption is applied one can gain azimuth and slope from the measured data of the prototype PV characterization station. Such gained azimuth and slope are presented in this research as measured results.

The whole database is processed in terms of extracting each cycle period with the data of azimuth, slope and MPP power. For each extraction the maximum value of MPP power is filtered, and its azimuth and slope are considered as Sun azimuth and slope. The additional adjustments must be made in order to be able to compare modeled and measured values of Sun position. The azimuth in conventional model is provided as 0° for South, -90° for East and +90° for West, so that the measured values must be subtracted by 90° in order to convert 0° for East and 180° for West to conventional values. This is calculated using equation (4). Also, the definition of Sun height is opposite to measured definition of slope. Therefore, the measured slope must be subtracted from +90° in order to gain conventional values of 0° for Sun on the Horizon and +90° for vertical position of Sun. This is calculated using equation (5).

(4) $$X'_d = X_d - 90°$$

(5) $$Y'_d = 90° - Y_d$$

The flow chart of data processing for providing azimuth and slope from measured data is presented in Fig. 5. Data processing uses assumptions as research conclusions described in [12, 13].

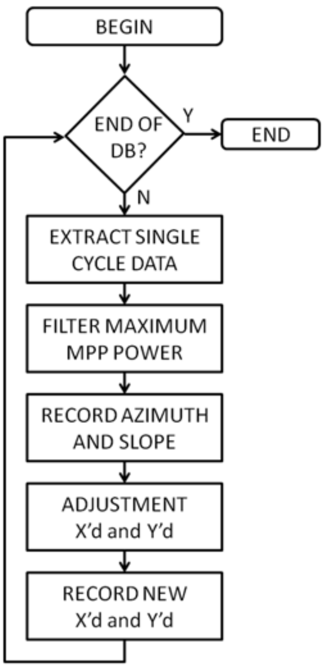

Fig.5. Flowchart of data processing for azimuth and slope

Modeled and measured Sun trajectory results

The comparison of modeled and measured position of Sun diagrams presented in Fig. 6-9 is provided on examples of days when measurement was very successful. Azimuth and slope have good matching, with rare deviations.

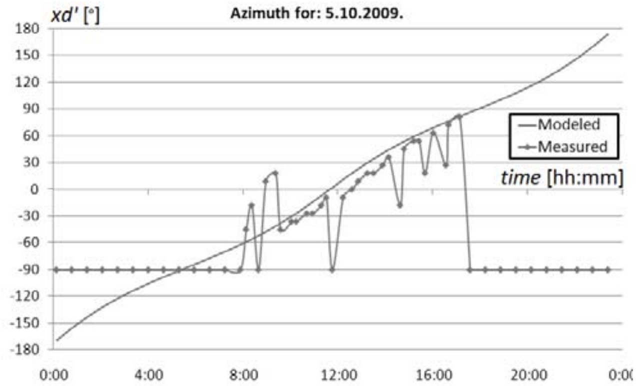

Fig.6. Modeled and measured azimuth for 5. 10. 2009.

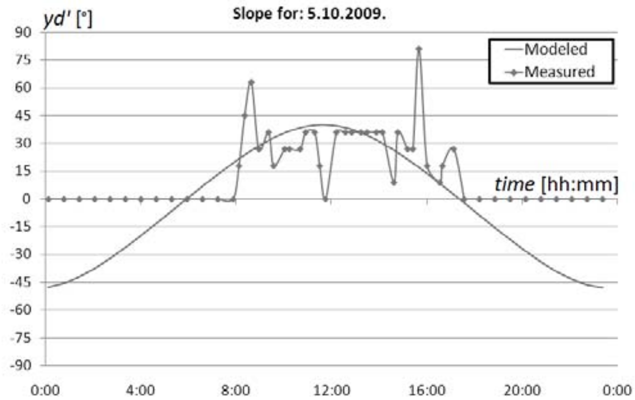

Fig.7. Modeled and measured slope for 5. 10. 2009.

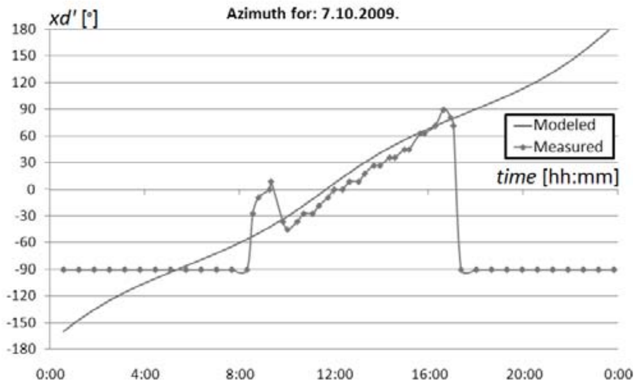

Fig.8. Modeled and measured azimuth for 7. 10. 2009.

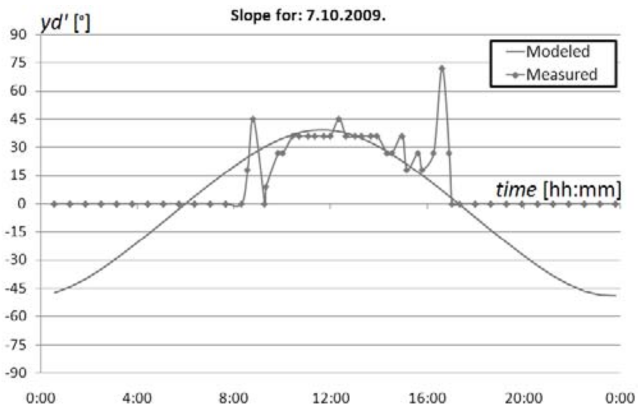

Fig.9. Modeled and measured slope for 7. 10. 2009.

In some cases the deviations were more common, but the matching of modeled and measured values for azimuth and slope is still present clearly demonstrated. Still visible differences require explanation. One example of such significant difference is 01. 11. 2009. presented in Fig. 10-11.

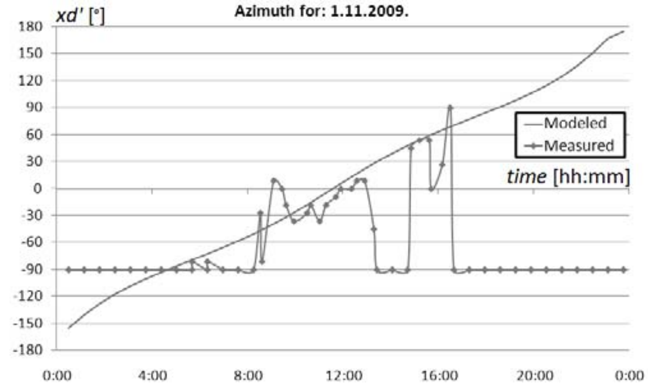

Fig.10. Modeled and measured azimuth for 01. 11. 2009.

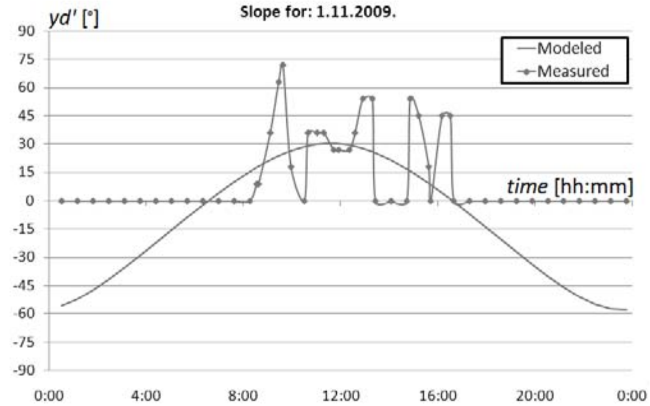

Fig.11. Modeled and measured slope for 01. 11. 2009.

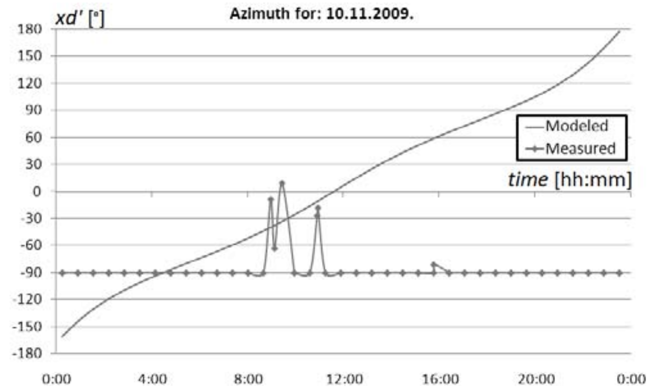

Fig.12. Modeled and measured slope for 5. 10. 2009.

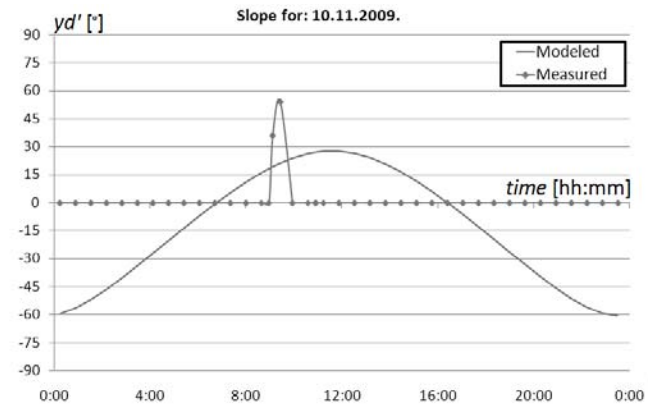

Fig.13. Modeled and measured azimuth for 7. 10. 2009.

In some cases the measurement results did not give adequate results. In these cases this modeling method can be considered as useless. One example of such case is 10. 11. 2009. presented in Fig. 12-13.

The analysis for all provided typical daily results are provided in next section.

Discussion of Sun trajectory results

The first and obvious flaw of modelling based on the measurements from the PV characterization station is that it is not able to provide azimuth and slope angles for night time. In case of using this measurement of azimuth and slope for PV system applications this flaw has no effect since the PV systems do not produce electrical energy in the night.

The next significant flaw is introduced in case of low irradiation. That is situation where sky is not clear so diffuse light is more dominant. This is somewhat present in Fig. 10-11, and especially in Fig. 12-13. In such case the PV production power is very small, and it can also introduce rather bad modelling of U-I characteristics and MPP operating point. Therefore, in such cases measurement error can provide significant errors while using this measurement of azimuth and slope. Still this flaw has rather low effect if used in PV systems since the PV energy production contribution in such periods is also low.

The common phenomenon in all cases of measured azimuth and slope is deviations at morning and evening hours. It can be seen on example of the results for 07. 09. 2009. In Fig. 6-7 where the time periods from 08:00 till 10:00 and then again from 16:00 till 18:00 have much larger errors in measured azimuth and slope to modelled values then the rest of the day. This was explained in second section and Fig. 2. In those particular hours the diffuse component of irradiation and reflexions from nearby buildings can significantly alter the measured azimuth and slope from conventionally modelled values. This measuring method will produce variant results if used on some other location with different surroundings. A unique analysis must be provided for each selected case of location and surroundings. Locations with as less possible dominant objects in surrounding are acceptable for this method of measurement of azimuth and slope.

If all examples of comparison are analyzed separately for azimuth and slope it can be concluded that the azimuth measurement provided much better and stabile results than the slope measurement. The range of azimuth values is 180° (East to West), while the range of slope is less than 90° (horizontal 0° to noon slope, always less than 90°). Therefore, the small change in input data can provide high error for slope.

In order to analyze this method in detail the further measurement data samples must be obtained, processed and analyzed. Some advanced conclusions about the measurement method for azimuth and slope will be possible when additional daily diagrams for measured and modelled azimuth and slope will be available. It will enable some general conclusions for location of prototype PV characterization station and probably some propositions for advances in data acquisition and measurement procedure.

Conclusion

The prototype PV characterization station is used to collect electrical and physical measured data. This measured information can be used for modelling the Sun trajectory. It can be seen that the results of azimuth and slope angles can be calculated from available data.

The conventional analytical models are rather precise when describing Sun trajectory for specific location. When modelled results provided from the prototype PV characterization station are compared to conventional analytical model results it can be seen that for certain conditions the results correspond well. In some cases determined in this paper prototype PV characterization station modelled results have significant error, but in these cases the PV system electrical energy is always low.

Therefore, if needed, this model can be used in most cases of PV systems where conventional model cannot be implemented, such as low processor performances of automation system for single-axis or dual-axis tracking system, etc.

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