Adaptive Algorithm for Solar Tracking in Photovoltaic Power Plants [★]

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Abstract: The diversity of the energy matrix in the world is one of the challenges demanding for new researches with alternative energy sources to bring flexibility and sustainability in their use. According with this panorama, the generation of electric energy with solar photovoltaic systems emerges as an important goal, and its technology is constantly advancing as an immediate solution for this quest of diversity. This paper presents a predictive control for a solar tracking algorithm to be used in single or double axis photovoltaic systems. The main characteristic and contribution of this algorithm represents a functional technological innovation because it does not use any sensors to determine the position of the Sun with respect to the panel. Such algorithm avoids unnecessary movements in cases of shadows on the panels caused by clouds, or some animal that could interfere on systems using the conventional sensors. The proposed solar time algorithm was tested and compared with field values, predicting the correct Sun position with accuracy of less than 1°. The qualitative and quantitative results presented here evidenced the real gain of the proposed algorithm-based system without any sensors to increase the generation gain of photovoltaic power plants.

Resumo: A diversidade da matriz energética no mundo é um dos desafios que exigem novas pesquisas com fontes alternativas de energia, para trazer flexibilidade e sustentabilidade ao seu uso. De acordo com esse panorama, a geração de energia elétrica com sistemas solares fotovoltaicos surge como um importante objetivo e sua tecnologia avança constantemente como solução imediata para essa busca pela diversidade. Este artigo apresenta um controle preditivo para que um algoritmo de rastreamento solar seja usado em sistemas fotovoltaicos de eixo simples ou duplo. A principal característica e contribuição desse algoritmo representa uma inovação tecnológica funcional, pois não utiliza nenhum sensor para determinar a posição do Sol em relação ao painel. Esse algoritmo evita movimentos desnecessários em casos de sombras nos painéis causadas por nuvens ou algum animal que possa interferir nos sistemas usando os sensores convencionais. O algoritmo de tempo solar proposto foi testado e comparado com os valores de campo, prevendo a posição correta do Sol com precisão menor que 1°. Os resultados qualitativos e quantitativos apresentados aqui evidenciaram o ganho real do sistema baseado no algoritmo proposto sem nenhum sensor adicional para aumentar o ganho de geração de usinas fotovoltaicas.

Keywords: Adaptive Algorithm; Solar Tracking; Prediction; Photovoltaic Systems.

Palavras-chaves: Algoritmo Adaptativo; Rastreador Solar; Predição; Sistema Fotovoltáico.

1. INTRODUCTION

Currently, there are several socio-environmental problems resulting of the world energy matrix mostly based on primary energies derived from oil, coal and atomic fuels. This approach raises a growing concern about the impact of these non-renewable and polluting forms of energy as the energy demand has increased considerably over time.

With the emergence of photovoltaic panels in the energy market, power generation becomes a technology increasingly present in our realities. The most remarkable side of the photovoltaic power comes directly from the Sun being converted into electricity through several photovoltaic modules of solar cells, without any other meaningful form of intermediate energy (Farret and Simões, 2006).

To have the best generation efficiency the approach adopted in many commercially available systems is the use of solar trackers in such a way to increase the efficiency of the photovoltaic generation plant. As the Sun position changes along the day, the energy delivery from a fixed photovoltaic panel becomes much smaller when compared to the same model of panel equipped with a solar tracking system.

Solar trackers are device designed to put a photovoltaic (PV) panel in frontal orientation to the Sun. Solar daily tracking can increase the PV power generation by 40% per year compared to a fixed angle module optimized for the region or up to 70% compared to a horizontally fixed PV (Mousazadeh et al., 2009). Solar panel tracking is not possible without an effective pointing system. This paper discusses the development of an algorithm to track the Sun position sensors using one or two-axis photo-tracked systems to establish the best Energy capture and reliability since the system does not carry any physical sensors.

2. METHODOLOGY

The literature algorithms can be classified into two types, the first group use simpler algebraic expressions and the second group contain more complex algorithms that give the precise location (latitude and longitude of the location) and an immediate instant of observation Grena (2008). These algorithms calculate the local coordinates for which the panel should be aimed for a better utilization of the solar radiation capture known as Solar Position Algorithm (SPA), as described in detail by Reda and Andreas (2004). To calculate and develop the solar position algorithms for photovoltaic applications, the positioning equations were simplified from Grena (2008); Reda and Andreas (2004); Suria and Idris (2015) and Ramos (2015) with a the Matlab software algorithm for their development and validation MATHWORKS (2016).

2.1 Equation of the Time

Because of the factors associated with the Earth's orbit around the Sun, the Earth's orbital velocity varies throughout the year, and the following equation of time (ET) can be used for data correction about the eccentricity of the Earth's orbit and inclination of its axis. Throughout the year, the average length of a day is 24 hours. Thus, the values of can be approximately expressed from the following equations:

$$B = (284 + Nd)\frac{360}{365} \qquad (1)$$

$$ET = 9.87\sin(2B) - 7.3\cos(B) - 1.5\sin(B) \qquad (2)$$

where ET is Equation of time (degrees), B in (degrees) and Nd is the number of days since the beginning of the year (days).

The graphical representation in Fig. 1 plots an annual variation of 30 minutes and, for the most critical points, this variation is of 15 minutes. The adjustment in the calculations is necessary to obtain the most acceptable precision of the solar position.
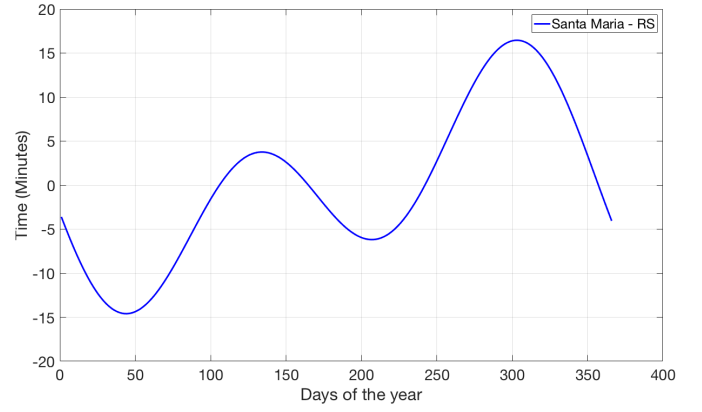

Figure 1. Annual time variation.

2.2 Longitudinal correction

The time as we know is the standard clock counted from a selected meridian near the center of a time zone, or from the standard Greenwich meridian located at the longitude 0°. Only a sundial measures the true local time, it is important to make the longitude correction through the 3.

$$TC = 4(Longitude - LSTM) + ET \qquad (3)$$

where TC is a Time Correction factor, $LSTM$ is a Length of the Standard Meridian for the location and ET is Equation of Time (degrees).

2.3 Solar angles

The Earth makes a complete rotation around its own axis every 24 hours, and a revolution around the Sun of approximately 365.25 days. This revolution is not circular, resulting from an elliptical trajectory with the Sun in the middle, as shown in Fig. 2. The eccentricity of the Earth's orbit is very small, so the Earth's orbit around the Sun is almost circular.
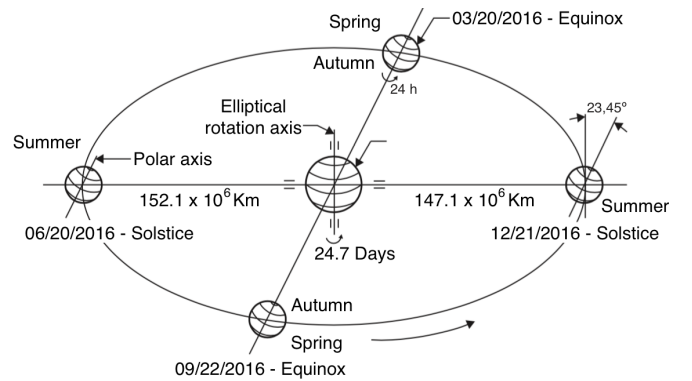

Figure 2. Movement of the earth around the Sun.

The distances Earth - Sun, R, in the perihelion (lower distance, on January 3) and in the aphelion (longest distance, July 4) were obtained by Garg Garg (1982).

$$R = a(1 \pm e) \qquad (4)$$

where a is a distances Earth - Sun = 149.5985×10^6 km and $e = 0.01673$.

The positive sign in 4 is for the distance Earth - Sun, when the earth is in the aphelion position, and the negative sign

is to the perihelion position. The solution of 4 gives the values for the longest distance equal to 152.1×10^6 km and for the shortest distance equal to 147.1×10^6 km.

The most obvious visible movement of the Sun that easily can be seen when looking at the sky is that it moves daily in an arc, reaching its highest point at noon. The situation of the differences of the ways and declinations of the Sun during the year in its equinoxes and solstices is verified in Fig. 3.
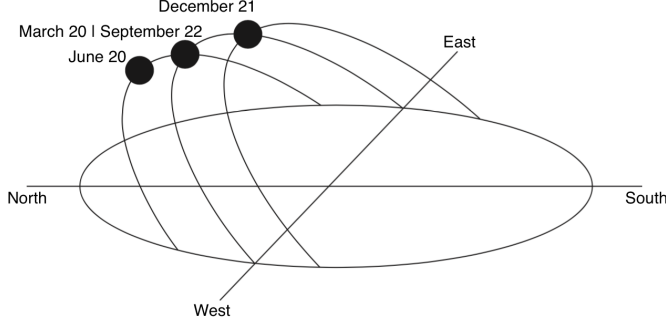

Figure 3. Annual changes in the position of the sun in the sky (southern hemisphere position).

2.4 Declination

As previously showed in Fig. 2, it is noted that the axis of rotation of the earth is inclined at an angle of 23.45^o from the elliptical axis of rotation. The declination varies from 0° at the spring equinox for $+23.45^o$ on the summer solstice, e 0° on the autumnal equinox, e -23.45^o on the winter solstice. The variation of the declination of the Sun throughout the year is presented in Fig. 4. The Figure makes reference to the south-brazilian city Santa Maria (Latitude: $29^o41'03''$ S, Longitude: $53^o48'25''$ W), RS, Brazil and its data is about this city because is where the study was proposed. The declination, δ, in degrees for any day of the year (Nd) and can be estimated approximately by 5:

$$\delta = 23.45 \sin \left[\frac{360}{365}(284 + Nd) \right] \qquad (5)$$
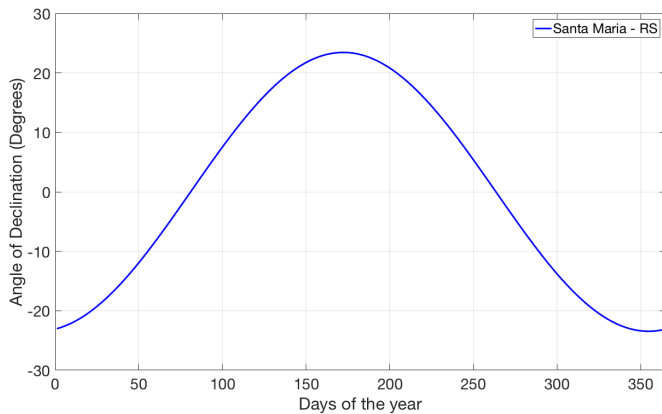
where Nd is a number of calendar days of the year.

Figure 4. Annual declination of the Sun.

2.5 Hourly angle

The hour angle is described by the following 6:

$$AH = 15 \left[\left(LT + \frac{TC}{60} \right) - 12 \right] \qquad (6)$$

where AH is a Hourly Angle (degrees), LT is a Local Time (degrees) and TC is a Time Correction factor.

2.6 Lifting angle

The Elevation angle is calculated by the following 7:

$$Elev = \arcsin \left[\sin \delta \sin \varphi - \cos \delta \cos \varphi \cos AH \right] \qquad (7)$$

where $Elev$ is a Elevation Angle (degrees), δ is Angle of Declination (degrees) and φ is a Latitude (degrees).

2.7 Zenith

The zenith denotes the (imaginary) point intercepted by a vertical (imaginary) axis drawn from the head of an observer (located on the earth's surface) and extending to the celestial sphere.

$$Zn = 90^o - Elev \qquad (8)$$

where Zn is a Zenith angle (degrees).

It can be seen in Fig. 6 that the zenith is a complement of the elevation angle.

2.8 Azimuth

The azimuth angle is calculated according to:

$$AZ = \arccos \left[\frac{\sin \delta \cos \phi - \cos \delta \sin \phi \cos(AH)}{\cos(Elev)} \right] \qquad (9)$$

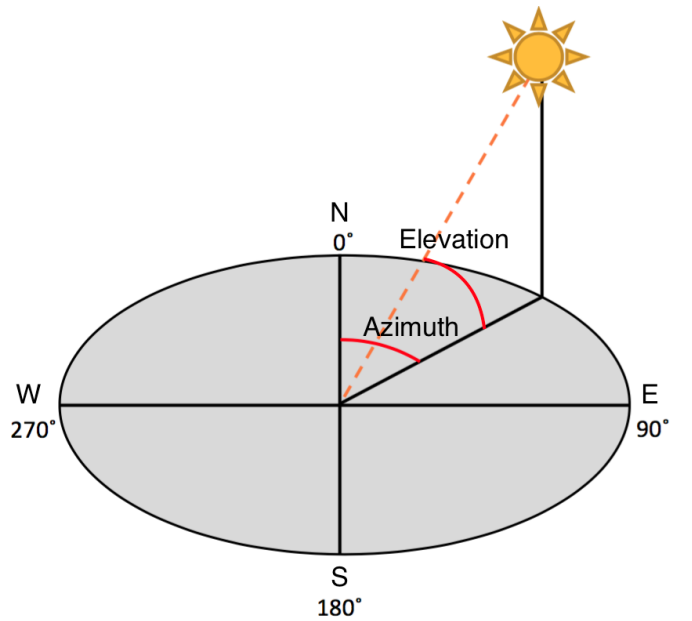where Az is Azimuth angle (degrees) and ϕ is a Longitude (degrees).

Figure 5. Azimuth angle

Equation 9 was used in the Matlab program to perform the predictive algorithm to drive a microcomputer to

implement validation tests with the data from the Solar Position Calculator (SPA) developed by Earth System Research Laboratory (ESRL) at the National Oceanic and Atmospheric Administration (NOAA) ESRL-NOAA (2016). The solar time algorithm used the azimuth angle and the elevation angle at noon solar that are used to orient the photovoltaic module, thus not requiring the use of any sensor to track the Sun. However, for use in a solar plant it is indicated to have some equipment to verify that the panels are in the position indicated by the algorithm.

3. PROTOTYPE DEVELOPMENT

To continue this study and discussions, it was necessary to build a real prototype, which made mandatory testing possible for practical proofs. The physical space used for the development of the prototype was in the Center of Excellence in Energy and Power Systems (CEESP) laboratory and the installation in the field was at National Institute for Space Research (INPE) in UFSM-Santa Maria, RS.

The macro idea of the complete system used in the experimental part of this research is presented, the block diagram in Fig. 6 illustrates the complete functioning of the solar tracking system. The flowchart presented shows how the control algorithm was implemented in the Matlab software, any other programming language can be used, however, this affinity was used.
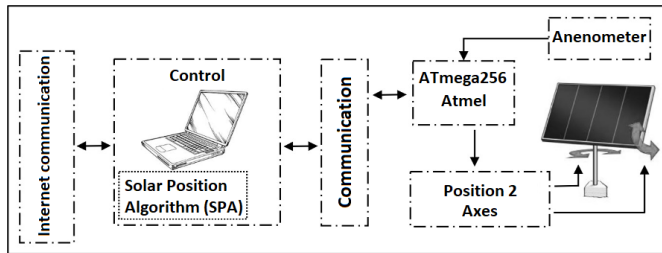

Figure 6. Prototype structure.

A mechanical structure was built that could move only a small photovoltaic panel for the initial tests. The other PV panel remained on a fixed slope calculated in advance, remember that the movement of the system with a solar tracker must be in zenith and azimuth angles so that the solar position algorithm in two axes can be tested. This structure consists of a base made with iron, in case strong winds or rain occur, it is not damaged or bent, thus making testing and obtaining experimental data impossible.

The upper base of the prototype was made of 10 mm acrylic, which serves to support the pipe that supports the support for the mobile system, where the servo motors and the photovoltaic panel were placed. Fig. 7 shows the structure with the metal base already complete.

The system is started first by asking the user for the geographic location information of the facilities, which are the longitude and latitude data. With these data properly entered, the control checks the wind speed.

If the wind exceeds the speed of 150 km/h, the solar tracker enters the safety mode that positions the panel horizontally to the Earth, and thus suffer the least possible drag force. The records are stored in a database and waited

Figure 7. Prototype.

5 minutes until the next reading, in such a way that the panels do not flicker at all times.

If the wind is normal, in this case, winds below 150 km/h, the controller enters the SPA, generating the output values sent to the servo motor. With these data, the electronic assembly moves the photovoltaic panel to the position calculated by the SPA. The zenith and azimuth values are stored in the database, waiting one minute to redo the control loop. It should be noted that setups, such as wind speed and waiting time at breaks, are adjustable in such a way as to allow the user to adapt their system to the best situation of each project.

The field installation for the practical tests was on the INPE terrace (Santa Maria - UFSM, RS), as shown in Fig. 8. The location is suitable for installations of test equipment, with easy access to a network point, with connection to the internet and the electric network, besides offering security. In addition, of course, this place receives sunshine for most of the day and year similar to the photovoltaic plant.
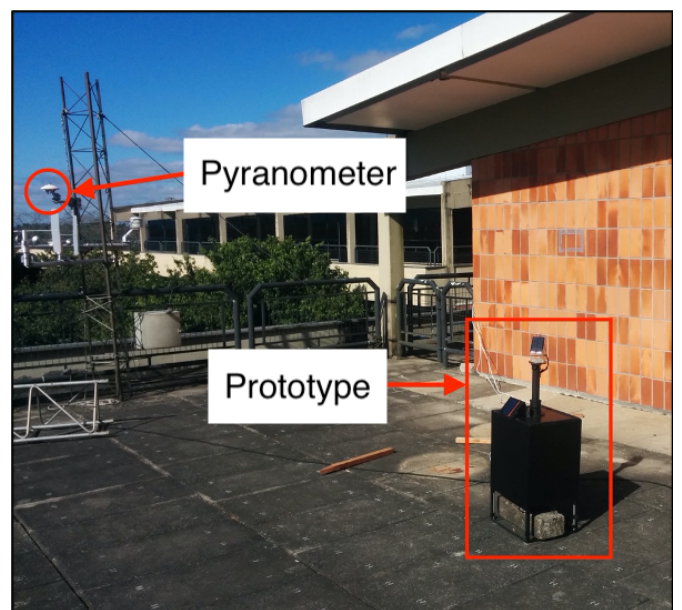

Figure 8. Prototype located on the roof of INPE.

With the values are already known from the time equation and local conditions, the longitudinal correction factor can be determined. Since time zone divisions are often political and economic, and not just geographic, this longitude correction between the local meridian and the time zone considered by the observer must be applied.

4. RESULTS AND DISCUSSION

To verify the developed system and its real precision of the solar tracking using comparisons of the data of the ESRL on a chosen day. We selected a start and end date, within which the system was running continuously, which was mid-afternoon of the day 07/14/2016 until the day 07/19/2016. As can be seen in Fig. 9, the algorithm showed good functioning since there was no failure during those days. The working day clarity time chosen in the algorithm is from 6 am to 8:59 pm each day. The algorithm runs every 1 minute, thus updating the tables for immediate use and saving to a database for later use. In this case, the data of 07/15/2016 were used for the validations, comparisons and discussions of the error levels in comparison with the table generated by the ESRL. This comparison ensures a satisfactory operating result of the solar tracker with up to 1° (one degree) as initially intended.
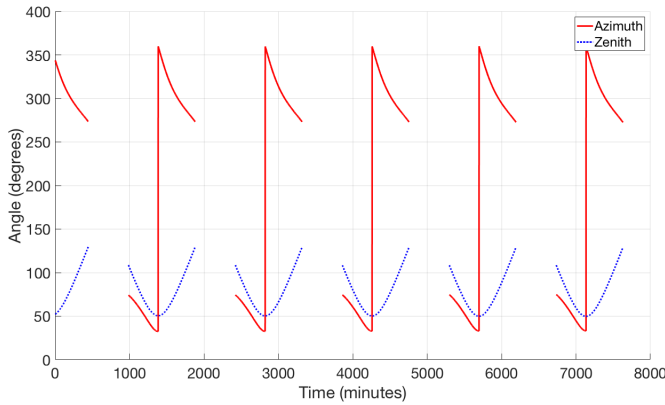

Figure 9. Uninterrupted test in the CEESP laboratory between Jul 14-19, 2016.

After the day has been selected 07/15/2016, The azimuth and zenith data table of this reference date on the website of the ESRL for the correct validations of the algorithm. Note that the data go from 0:00 a.m. hours until 11:59 p.m. of the day, noting that for the photovoltaic generation, the tracking schedule of the Sun does not happen during the night period in this proposed algorithm because the systems with photovoltaic panels need not be tracked at night.

As can be seen in the Fig. 10, the solar tracking algorithm ensures good accuracy at the azimuth angle over the entire tracking time. The algorithm went into operation at 6:00 a.m. in the morning and shut down at 8:59 p.m. each day, and it is possible to change the operating hours of the prototype via programming. The biggest value where this error happens is when the ESRL indicates 74.64^o and the proposed system calculates an angle of 73.75^o this difference is the error 0.89^o, therefore less than the maximum precision of the predicted error for this algorithm which is 1°.
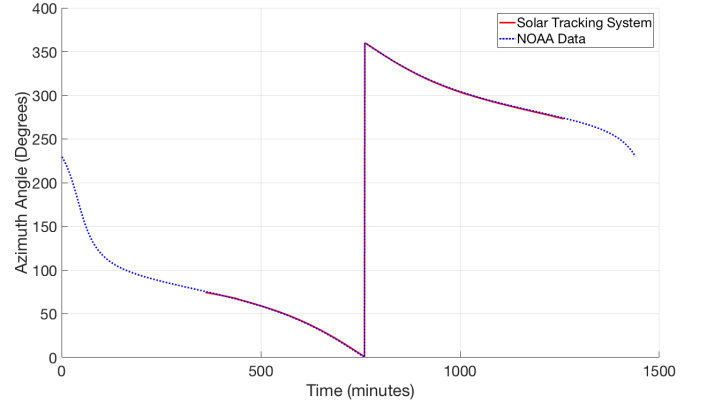

Figure 10. Azimuth angle comparison in Jul 15, 2016.

Fig. 11 depicts all points and their respective errors. The point of maximum error was in 369 minutes of the day 07/15/2016, which is 06 hours and 15 minutes where the 0.89^o. It was concluded that the predictive algorithm in the azimuth axis had a good accuracy of the tracing.
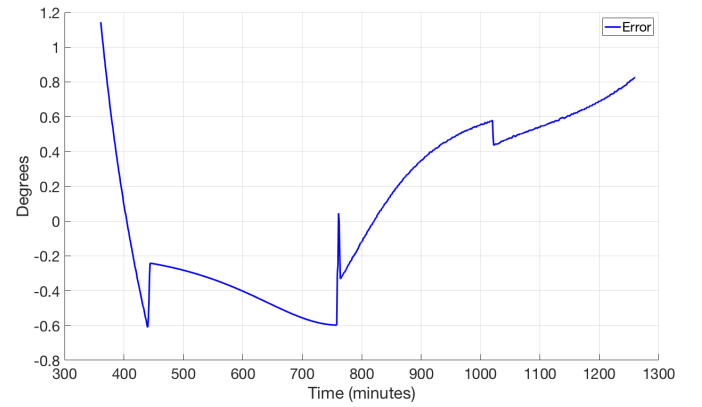

Figure 11. Azimuth angle error in Jul 15, 2016.

A similar comparison was then made with the previous one, using the data from the ESRL to compare the angles, but now with studies focused on zenith angle of solar tracking. It can be seen from Fig. 12 that the positioning indication was practically aligned with the data provided by the ESRL.
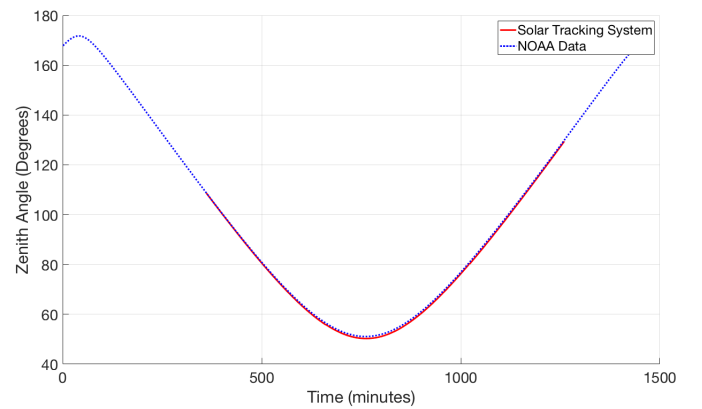

Figure 12. Comparison zenith angles in Jul 15, 2016.

The tracking algorithm had its most critical point in the 51.64^o in relation to the table generated in ESRL which is

of 52.49°. It is again noted that the biggest mistake was 0.85°.

Fig. 13 shows the most critical points of positioning, where the other errors can also be verified. With these results, it can be considered that the algorithm is suitable for the positioning of the panels according to the data of the ESRL, because no greater error was obtained than 1° in the zenith angle.
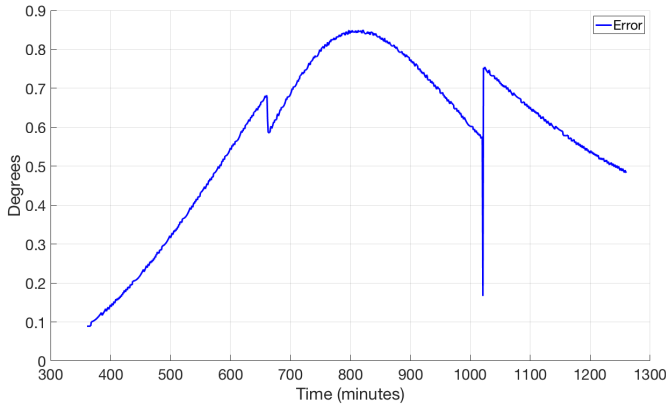

Figure 13. Zenith angle error in Jul 15, 2016.

5. CONCLUSION

Based on the bibliographical reviews and on experimental results, important conclusions were gathered about operation of a solar tracking algorithm for photovoltaic panels.

This paper presents a complete methodology for implementation of the algorithm in a two-axis solar tracking system for positioning of photovoltaic modules. As a term of comparison, these results showed that the prototype with the double-axis solar tracking algorithm present relatively similar measurement values when compared to the actual solar position of the Sun.

The solar tracking prototype assembled for this research was able to test the main factors of the control algorithm and of the entire proposed methodology. During the analysis, some factors such as the cost of the panels, the degradation, and the useful life were not taken into account. Such verification is outside the scope of this work, which focused only on proving the functioning of the development of a detailed methodology for an automated two-axis solar tracker for autonomous photovoltaic systems.

When comparing the data from this proposed algorithm with the National Oceanic and Atmospheric Administration (NOAA) Earth System Research Laboratory (ESRL) it is obtained an error of less than 1. The azimuth angle had an error greater than 0.89° and for the zenith angle it was 0.85°. So, it can be said that this solar pointing system can replace the usual tracking systems with errors not affected by mechanical constructions.

It is important to say that this method is recommended for installation of photovoltaic plants with two-axis tracking, especially in environments away from the equator as it was the case for simulations discussed in this paper. In different latitudes and longitudes, it not required additional corrections to the positioning algorithm because with only the location data, the adjustments and parameters operates it automatically allowing a great flexibility and low costs in its use.

6. RECOMMENDATIONS FOR FUTURE WORK

Recommendations for future works can be listed as:

(1) Use the Global Positioning System (GPS) to provide a more accurate reading of the latitude and longitude coordinates;
(2) Use of a GPS algorithm for the actual tracking system of a solar photovoltaic plant or a prototype to prove its effectiveness in all cases and verify that the solar tracker can withstand in various operational climates in a long run without any failures and that it really minimizes the manual supervision;
(3) Enhancement of the SPA algorithm so that it calculates a day earlier the best positioning of PV panels between the sunrise and sunset times, preparing in advance the panel triggering and turning it off at the exact times of the sun rise and set; such a procedure would minimizes tracking losses when there is not solar radiation;
(4) Another point that can be considered is the correction intervals of solar positioning with respect to other intervals such as for 1, 5, 10 or 15 - minute intervals.

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