Step tracking program for concentrator solar collectors

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Abstract. The increasing living standards in developed countries lead to increased energy consumption. The fossil fuel consumption and greenhouse gas effect that accompany the energy production can be reduced by using renewable energy. For instance, the solar thermal systems can be used in temperate climates to provide heating during the transient period or cooling during the warmer months. Most used solar thermal systems contain flat plate solar collectors. In order to provide the necessary energy for the house cooling system, the cooling machine uses a working fluid with a high temperature, which can be supplied by dish concentrator collectors. These collectors are continuously rotated towards sun by biaxial tracking systems, process that increases the consumed power. An algorithm for a step tracking program to be used in the orientation of parabolic dish concentrator collectors is proposed in the paper to reduce the consumed power due to actuation. The algorithm is exemplified on a case study: a dish concentrator collector to be implemented in Brasov, Romania, a location with the turbidity factor $T_R$ equal to 3. The size of the system is imposed by the environment, the diameter of the dish reflector being of 3 meters. By applying the proposed algorithm, 60 sub-programs are obtained for the step orientation of the parabolic dish collector over the year. Based on the results of the numerical simulations for the step orientation, the efficiency of the direct solar radiation capture on the receptor is up to 99\%, while the energy consumption is reduced by almost 80\% compared to the continuous actuation of the concentrator solar collector.

Introduction

The continuous growth of the world population is accompanied by the increase of the energy consumption and of the greenhouse emissions. The improving life standards and the use of a large number of electric devices lead to the increase of power consumption that puts a supplementary burden on the fossil fuel use and, finally, on the environment. Besides, in metropolitan cities, more than a quarter of the total annual electricity consumption is used for heating and cooling.

One way to reduce the fossil fuel consumption and the greenhouse effects consists in using renewable energy systems to produce energy for heating and cooling machines. Therefore, the use of solar energy for heating and cooling has become a much addressed topic in the last years.

The solar energy can be converted into solar thermal energy by using solar collectors. In the case of planar solar collectors, the working fluid temperature is in the range 40°C to 60°C, while the working fluid temperature is higher than 80°C for concentrator collectors [1]. The solar thermal systems with solar collectors can be used to provide domestic hot water, heating or cooling. The temperature of the working fluid is approximately 50°C in the first case, 60°C for heating, while, for cooling, the working fluid has a temperature higher than 80°C. Therefore, a different type of solar collector has to be used in...
each case. For instance, a flat plate collector is preferred to produce only domestic hot water, while for producing domestic hot water and heating it is better to use a vacuum tube collector. A solar thermal system for heating and cooling purposes uses, mainly, concentrator solar collectors.

The main types of concentrator solar collectors are: parabolic trough collector, parabolic dish collector, and with central receiver [2]. In order to capture the beam solar radiation, the concentrator collectors are equipped with tracking systems, which ensure orientation around one or two axes [3][4]. The parabolic trough collector uses a mono-axial tracking system, while the parabolic dish collector and the one with central receiver use for orientation bi-axial tracking systems. The following types of bi-axial tracking systems are used in the solar orientation: a. azimuth tracking system (figure 1,(a)); b. pseudo-azimuthal tracking system; c. equatorial tracking system (figure 1,(b)), and d. pseudo-equatorial tracking system [5].

![Figure 1. Bi-axial tracking systems [5]: (a) azimuth; (b) equatorial](image)

The azimuth tracking system is characterized by a good orientation accuracy towards sun, but it is a major consumer of power due to the request of simultaneous actuation of the two motions. In the equatorial and pseudo-equatorial tracking systems, the two motions are decoupled, the orientation accuracy is good, but the stability is not as good as in the case of the azimuth tracking systems.

So far, the solar thermal systems used for cooling were built with flat plate collectors or vacuum tube collectors [6]. Their disadvantages are referring to the need of a large number of collectors and/or of large exposure surfaces. The parabolic dish collectors can also be used for cooling purposes, but the main problem is to find solutions adaptable to urban architectural integration.

Usually, the parabolic dish collector uses for orientation an azimuth tracking system. In this case, the collector orientation is made continuously, consuming power. The paper is proposing an algorithm for establishing a step tracking program for the azimuth tracked parabolic dish collector, meant to reduce the power consumption during orientation process. The algorithm is applied to get the orientation program for the case of a parabolic dish solar collector to be implemented in Brasov, Romania. The numerical simulation results led to a number of 60 sub-programs for orientation of the collector during the year. These sub-programs are determined for a maximum tracking error equal to 1.74° (or 3 mrad). By using this orientation program, the amount of direct solar radiation captured by the collector receiver is about the same with the amount of available solar radiation, while the power consumption is reduced about 5 times.

2. Algorithm for the Step Tracking Program
The parabolic dish collectors use for orientation azimuth tracking systems due to the need of accuracy and stability during operation. Usually, the orientation is done continuously, involving power consumption. So far, the parabolic dish concentrator collectors use light sensors to follow continuously the sun on the sky. The reflector is moving with an angle equal to the hour angle (15°/
hour). In order to minimize the power consumption due to the tracking motion, the step orientation of
the dish reflector with the azimuth and altitudinal angles, $\psi^*$ and $\alpha^*$ (see figure 2) is recommended
in the paper. The angles that describe this orientation are presented in the reference system that contains
the horizontal plane that is orthogonal to the Earth surface in the observer’s position and the local
vertical (figure 2).

Using as input data the size of the parabolic dish collector, the step tracking program can be
developed based on the following algorithm:

1. the unit vector of the sunray, $[e_{SR}]_{X_0Y_0Z_0}$ [7] is written in the azimuth reference system that is
   considered as the fixed coordinate system $QX_0Y_0Z_0$ (figure 2):

   \[
   \begin{bmatrix}
   \cos \alpha \cdot \sin \psi \\
   -\cos \alpha \cdot \cos \psi \\
   \sin \alpha
   \end{bmatrix}
   \]
   (1)

   where $\psi$ is the azimuth angle, the motion being made from East to West, and $\alpha$ - the altitudinal angle.

2. the unit vector of the normal to the collector’s surface is modelled similarly, in the local
   coordinate reference system that is attached to the tracking system. The angles of the sunray in the
   tracking reference system are denoted by $\psi^*$ and $\alpha^*$, in order to differentiate them from the same
   angles measured in the fixed coordinate system.

3. the incidence angle between the sunray unit vector and the normal to the collector’s surface, $\nu$ is
determined as “$\cos \nu$”; the angle expressed in the local coordinate system is given by the following
   relation [7]:

   \[
   \cos \nu = \cos \alpha \cdot \cos \alpha^* \cdot \cos(\psi - \psi^*) + \sin \alpha \cdot \sin \alpha^*.
   \]
   (4)

Figure 2. The orientation angles for the parabolic dish solar collector.
4. the time range at which the tracking system is operated is further established. The step duration is determined by comparing the incidence angle with its acceptable maximum value.

5. the day of the year which has the maximum influence on the incidence angle is determined the seasons and sub-programs for the actuation of the tracking system are established starting from the four significant days of the year: spring equinox, day no. N = 82; autumn equinox, N = 265; summer solstice, N = 172, and winter solstice, N = 356. A season represents a number of days in which the same orientation program can be used. The incidence angle is computed for all these days.

The solar hour (i.e. the time defined by the sun position on the sky) is used in angles calculation. The following variables are different when using solar time versus local time: the day number (N), the longitude, the time zone, the daylight saving time concept and the local time [9].

The application of the algorithm is further exemplified on a parabolic dish collector located in Brasov region. In order to integrate the parabolic dish collector in the built environment, the diameter of the collector’s reflector is set up at 3 m.

3. Case Study

The incidence angle for the step orientation is computed for the following input data:
- the implementation location is Brașov/Romania (with the latitude $\phi = 45.583^\circ$N and the turbidity factor $T_R = 3$ [8]);
- according to the technical literature, the maximum acceptable value for the incidence angle is $1.74^\circ$ (or 3 mrad) [10].

The variations of the azimuth ($\psi$) and altitudinal ($\alpha$) angles for Brasov in solstice and equinox days are established based on equations (2) and (3), being graphically presented in figures 3 and 4.

To find out the optimal tracking program for the parabolic dish collector, the following steps have to be accomplished:
A. setting up the optimum angle for the daily motion;
B. setting up the optimum angle for altitude, and
C. setting up the seasons and the number of sub-programs for one year.

![Figure 3. The variation of the azimuth angle in time, for the representative days.](image-url)
Figure 4. The variation of the altitudinal angle in time for three of the representative days.

A. The daily motion (the azimuth angle)

In order to find out the optimum step angle for the orientation of the parabolic dish collector, equations (2) and (3) are used, in which the angles $\omega$ and $\delta$ are used as variable parameters. To determine the duration of step tracking for the daily motion, calculations were performed for step durations of 4, 6, 8, 9, 10 and 12 minutes. In case of a step orientation, during one step (i.e. for 6 min) the value of the hour angle $\omega^*$ is kept constant. The diagrams of the hour angle variation for both types of orientation are presented superposed in figure 5.

Figure 5. The variation of the hour angle vs. solar hour for the summer solstice day.

The day with the highest value of the incidence angle can be obtained by numerical simulations that are performed for the four representative days of the year: the spring equinox (day number $N = 82$), the summer solstice ($N = 172$), autumn equinox ($N = 265$) and winter solstice ($N = 356$). The incidence angle is determined based on equation (4) and the following angles: solar azimuth ($\psi$), solar altitude ($\alpha$), surface azimuth ($\psi^*$) and surface altitude ($\alpha^*$) angles. The simulation results highlight that the incidence angles for the summer and winter solstice have the same values, and that the worst days in terms of the incidence angle are the equinox days, (figure 6).
Figure 6. The variation of the incidence angle vs. the step duration during equinox and solstice days.

The results of the numerical simulations for the two equinox days highlight that the maximum allowed value of the incidence angle for the solar dish collector (\( \nu < 1.54^0 \)) is reached at a step time of 8 minutes. In case of a step time equal to 9 minutes, the value for the incidence angle is \(1.78^0\) and, therefore, the reflected solar radiation can’t reach the receiver (as seen in figure 7).

Figure 7. The variation of the incidence angle vs. the step duration for the equinox days.

B. The seasonal motion (the altitudinal angle)
The altitudinal angle \((\alpha^*)\) is obtained considering the previously established value of the surface azimuth angle, \(\psi^*\) as constant. The altitudinal angle is obtained for the most important days throughout the year: the equinoxes and the solstices based on equation (4). The diagrams built for the incidence angle are presented in figure 8. The diagrams analysis highlights the optimum value of the step duration for the spring equinox day as 8 minutes, and for summer solstice as 9 minutes.
C. Seasons and sub-programs
The next step in designing the tracking program consists in defining the seasons.
The seasons are delimited as follows: the spring equinox day is considered, the same values for $\alpha^*$, $\psi^*$ being taken into account also for the days before and after the considered day ($N = 80...84$); for this period of time, the incidence angle is computed and compared to the maximum allowed value, 1.74°. The diagram of the incidence angle for the season containing the spring equinox is presented in figure 8.(a); similarly, the solstice season is delimited in figure 8.(b).

![Incidence angle for different days of the year](image)

**Sub-program P15**

![Incidence angle for different days of the year](image)

**Sub-program P30**

**Figure 8.** The incidence angle for two representative days of the year: (a) spring equinox day; (b) summer solstice day.

The other seasons for the year division can be similarly determined. The relevant data representing the number of sub-programs, the number of days in a sub-program, the step duration are systematized in Table 1.
Table 1. Step tracking program

| Sub-program | Step duration [min.] | Values for $\alpha^*$, $\psi^*$, identical to the day no. | No. of days with the same sub-program N | Number of days |
|-------------|----------------------|----------------------------------------------------------|----------------------------------------|----------------|
| P0          | 9                    | 356                                                      | 344…2                                  | 23             |
| P1          | 9                    | 8                                                       | 3…11                                   | 9              |
| P2          | 9                    | 15                                                      | 12…17                                  | 6              |
| P3          | 9                    | 20                                                      | 18…22                                  | 5              |
| P4          | 8                    | 25                                                      | 23…28                                  | 6              |
| P5          | 8                    | 31                                                      | 29…34                                  | 6              |
| P6          | 8                    | 37                                                      | 35…40                                  | 6              |
| ...         | ...                  | ...                                                     | ...                                    | ...            |
| P12         | 8                    | 68                                                      | 66…70                                  | 5              |
| P13         | 8                    | 73                                                      | 71…75                                  | 5              |
| P14         | 8                    | 78                                                      | 76…80                                  | 5              |
| P15         | 8                    | 82                                                      | 81…83                                  | 3              |
| P16         | 8                    | 86                                                      | 84…88                                  | 5              |
| P17         | 8                    | 91                                                      | 89…93                                  | 5              |
| ...         | ...                  | ...                                                     | ...                                    | ...            |
| P27         | 9                    | 143                                                     | 141…145                                | 5              |
| P28         | 9                    | 148                                                     | 146…151                                | 6              |
| P29         | 9                    | 156                                                     | 152…160                                | 9              |
| P30         | 9                    | 172                                                     | 161…185                                | 25             |
| P31         | 9                    | 190                                                     | 186…194                                | 9              |
| ...         | ...                  | ...                                                     | ...                                    | ...            |
| P41         | 8                    | 260                                                     | 258…262                                | 5              |
| P42         | 8                    | 265                                                     | 263…267                                | 5              |
| P43         | 8                    | 270                                                     | 268…272                                | 5              |
| ...         | ...                  | ...                                                     | ...                                    | ...            |
| P57         | 9                    | 326                                                     | 324…328                                | 5              |
| P58         | 9                    | 331                                                     | 329…334                                | 5              |
| P59         | 9                    | 338                                                     | 335…343                                | 5              |

The comparison between the step and the continuous orientation can be made in terms of the efficiency of solar radiation capture and the power consumption in the tracking process. The amount of available direct solar radiation $B_M$ can be obtained as follows [7]:

$$B_M = B_0 \times \exp\left(-\frac{T_R}{0.9 + 9 \times \sin \alpha}\right), \quad (5)$$

where $B_0$ is the extraterrestrial solar radiation, and $T_R$ is the turbidity factor.

The direct solar radiation that is captured by the dish’s receptor can be estimated based on equation (6):

$$B_{DC} = B_M \cos \nu, \quad (6)$$

where: $B_{DC}$ is the direct solar radiation received by the dish collector, and $B_M$ is the available direct solar radiation, modelled by Meliss (equation 5) [11].

The diagrams for the variation of the available solar radiation and the direct radiation received by the dish collector in the spring equinox and summer solstice days are comparatively presented in figure 9.

After determining the direct solar radiation received by the solar dish collector, the receiving efficiency, defined as the ratio between the energy received by the dish collector ($E_{BDC}$) and the available energy from the direct solar radiation ($E_{BM}$) is given by relation (7):
\[ \eta = \frac{E_{\text{rec}}}{E_{\text{in}}} \, [\%] \]  

Based on the numerical simulations, the receiving efficiency in the winter solstice day is 98.41\%, in spring equinox day is 98.51\%, in summer solstice is 98.39\%, and in autumn equinox is 98.47\%.

The power consumption depends on the step duration and type of actuation. Thus, for a step of 8 minutes and a tracking system with electric actuation, the power consumption is reduced about 5 times versus the continuous orientation.

**Figure 9.** Direct solar radiation received by the solar dish collector: (a) spring equinox day; (b) summer solstice day.

### 4. Discussions and Conclusions

The dish concentrator collectors use biaxial tracking systems for orientation. Therefore, this type of collector requires high orientation accuracy, which is assured with a continuous tracking motion that is accompanied by a high power consumption. In order to reduce the electric energy consumption during orientation, the paper proposes and develops a step program for the accurate orientation of concentrator collectors.
Based on input data as the maximum value of the incidence angle and the collector implementation area, the paper proposed algorithm allows the power consumption minimization by using a step orientation of the dish concentrator collectors with azimuth tracking system. The algorithm can be adapted for the other types of tracking systems, as well (equatorial, pseudo-equatorial and pseudo-azimuthal).

This step tracking program can be used with good results, mainly in temperate climate, with heating and cooling needs.

The results of the numerical simulations for Brasov region highlight the following conclusions: in case of a parabolic dish collector the step tracking program contains 60 sub-programs (see table 1); for each sub-program, the altitudinal angle has a step duration of 8 minutes, and in case of azimuth angle the step time is equal to 8 or 9 minutes. The shortest sub-program has 3 days, it starts in the day number N = 81 and ends in the day N = 83 (see table 1, P15). The broadest sub-program totalizes 25 days, it starts in the day number N = 161, and ends in the day N = 185, and corresponds to the summer solstice (see table 1, P30). Among the 60 step tracking sub-programs, 12 sub-programs have the step time from 9 to 9 minutes, and the others have the step time equal to 8 minutes.

In order to find out the orientation efficiency in terms of the quantity of the solar radiation received by the parabolic solar dish collector that will be implemented in Brasov area, the ratio between the received energy and the available energy was calculated for different days of the year.

The simulation results highlight a reduction with only 1% of the solar energy received by the parabolic dish collector in case of a step tracking program versus the continuous orientation. The power consumption for orientation is reduced up to 5 times versus the continuous tracking, depending of the step duration and type of actuation.

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