Design and Implementation of an Intelligent Solar Power Plant Based on Fuzzy Logic

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Abstract—Solar energy has been accepted as an alternative source of energy worldwide recently. Current researches and markets have shown that Solar Photovoltaic (PV) is the fastest growing and most promising form of renewable energy used in generating electricity. This paper presents an intelligent sun tracking system in which photo-resistors (sensors) are used to determine the direction of the sunlight along with wind sensors to specify the direction of the wind. Due to their high performance and low expense, these sensors have been preferred and used. An algorithm based on fuzzy logic is designed to implement the controlling system considering all the various meteorological conditions. The hardware structure of the system consists of an AVR microcontroller; hence the small size of the whole controlling system. The solar cell is used as the power supply of the controlling system. Finally, an intelligent solar power plant is implemented by means of the techniques mentioned above.

Keywords: Solar Plant, Fuzzy Logic, AVR Microcontroller, Renewable Energy

Nomenclature

\[ T_V = \text{vertical error} \]
\[ T_H = \text{Horizontal Error} \]
\[ V_0 = \text{DC offset voltage} \]
\[ V_S = \text{output voltage of the photo resistor sensors} \]
\[ \theta_0, \theta_H = \text{the angle of the sunlight with cell} \]
\[ A/D = \text{ Analog to Digital Convertor} \]
\[ dT_H, dT_V = \text{error variation} \]

I. Introduction

The sun’s energy travels to the earth in the form of electromagnetic radiation with a wide spectrum of frequencies. Solar energy is often expressed in watts per square meter (W/m²) or watt hours per square meter (Wh/m²). The amount of energy available from the sun outside the atmosphere of the Earth is approximately 1367 W/m² [1]. However, the solar radiation reaching the Earth is less than this value. This is because of other energies entering the atmosphere, which lower the solar radiations, through scattering and absorption, down to about 1000 W/m². Although the global irradiation on the surface of the Earth can be as high as 1000 W/m², the available irradiation is usually considerably lower than this maximum value due to the rotation of the Earth and different weather conditions. At any particular time, the available solar energy primarily depends upon how high the sun is in the sky and what the current cloud conditions are. The available amount of solar energy also depends upon the location. In general, the amount of usable solar energy is contingent upon the available solar energy, other weather conditions, the technology utilized, and the intended application. The science of using solar energy has exceedingly developed during last decade due to the harmful effects of fossil fuels [2]-[4]. This paper is going to concern itself specifically with photovoltaic cells and solar concentrating power plants. In less modern solar power plants, fixed cells are used to concentrate solar energies; however, the fixed conditions of the cells lead to the loss of some energy during the morning and evening each day which inevitably decreases the efficiency of such solar power plants. As previously studied and demonstrated, the photovoltaic cells are devices that convert sunlight to electricity and reach their maximum efficiency if the sun-tracking procedure is carried out sufficiently well [5]. Solar trackers are, traditionally, open loop systems but in order to increase the efficiency of such plants, closed loops ought to be considered. Some algorithms have been designed to implement the sun tracking system [6]. Among these algorithms, fuzzy logic is one of the best ones used to control such plants [7].

If a sunlight tracking system is used, the amount of energies absorbed will be much more than when fixed solar cells are employed. The efficiency of traditional fixed systems is about 8.1% which can increase up to 18.5% by using intelligent systems [8].

Not only does the designed power plant consist of a sun tracking system but also it is equipped with sensors determining both the direction and intensity of the wind so that under specific weather conditions, such as storms, the system will be able to handle maximum amounts of energy as well as keep its mechanical units safe.

This paper aims to design and implement an intelligent solar power plant by means of tracking sunlight systems, through the data they provide as to the direction and strength of any given wind, based on fuzzy logic.
II. The Circuit

The controlling and electrical units of the solar cells consist of three main parts, each with its own duty. The function of the whole process, therefore, will be explained in the following parts:

a) Photo sensors
b) Wind detecting sensors
c) Microcontroller and motor drivers
d) Algorithm

II.1. Photo Sensors

The applied sensors are based on a straightforward, highly accurate idea: the relation between the angles of a light source. The efficiency of the solar cells is directly related to the angle of the radiations of the sun. The main task of the sensors is to accurately track the sunlight which is always perpendicular to the cells. The proposed design consists of four light-sensitive photo-resistors, mounted on the solar panel and placed in an enclosure. The four light detectors are divided into two legs and screened from each other by non-transparent plates which are perpendicular to each other as shown in Fig. 1. Each of the legs includes two photo-resistors the first of which is used to track the sun horizontally with a stepper motor and the second of which allows the vertical tracking of the sun through a DC motor.

![Fig. 1. Position of photo resistors](image)

Each pair of sensors is associated with a differential amplifier. The outputs $T_V$ and $T_H$ correspond to the vertical and horizontal errors; further, they define the feedback which is used as the variables of the fuzzy input for the fuzzy controller in order to generate the vertical and horizontal commands respectively in terms of speed and direction to an appropriate DC and stepper motor. Equation (1) gives the expressions of $T_V$ and $T_H$ calculated by the microcontroller input circuit which is shown in Fig. 2, the $V_0$ offset being added to obviate a bipolar power supply.

$$
T_V = \frac{R_2}{R_1} (V_{S4} - V_{S3}) + V_0 \\
T_H = \frac{R_2}{R_1} (V_{S2} - V_{S1}) + V_0
$$

Whereat:

- $R_1$ and $R_2$ are the resistors of the differential amplifiers.
- $V_{Si}, i=1, 2, 3, and 4$, signify the output voltage of the photo resistor sensors.
- $V_0$ denotes the DC offset voltage.

![Fig. 2. Schematic of sensors circuit](image)

If $T_V$ is greater than $V_0$, the angle of the sunlight with cell ($\theta_V$) will be less than 90 degrees; therefore, the solar cell should be turned from south to north. However, if $T_V$ is less than $V_0$, the solar cell should be turned from north to south. Meanwhile if $T_V = V_0$, the sunlight must be perpendicular to the cell (i.e. $\theta_V = 90$ degrees). Similarly, if $T_H$ is greater than $V_0$, the angle of the sunlight with cell ($\theta_H$) will be less than 90 degrees; consequently, the solar cell should be turned from east to west. In case $T_H$ is less than $V_0$, the solar cell should be turned from west to east. $\theta_V$ and $\theta_H$ are illustrated in Fig. 3.

The desirable position of a solar cell can be achieved when both $\theta_V$ and $\theta_H$ equal 90 degrees.
II.2. Wind detecting sensors

Sensors were utilized to determine the intensity and the direction of the wind. In some cases, the solar cells must be perpendicular to the direction of the wind to achieve maximum solar energy. In such cases, a large amount of force is imposed on the mechanical units and on the solar cell. As a result, the control system must perform a trade-off between achieving the maximum solar energy and maintaining the safety of the units. That is, when the force of the wind exceeds the amount that the mechanical unit can withstand, the control system will align the solar cell with the direction of the wind, and after the gale has abated, it will continue to detect the maximum solar energy.

II.3. Microcontroller and motor drivers

This unit is mainly composed of a high-performance, low power 8-bit AVR microcontroller with advanced RISC architecture. The microcontroller comprises an internal 8-channel 10-bit A/D convertor. First, the output signal of the photo-resistors is amplified by the amplifiers and subsequently linked to the ADC0 and ADC1 pins of the microcontroller as shown in Fig. 2. The microcontroller reads the analogue value of the sensors by means of its internal A/D convertor and compares it with $V_0$; next, the essential orders are sent to the motor drivers for sunlight tracking.

In order to turn the solar cells horizontally and vertically, a DC motor and a hybrid stepper motor are used respectively.

II.4. Algorithm

In most research literature, a fuzzy controller system is commonly defined as a system that emulates a human expert. In this case, the knowledge of the human operator is put in the form of a set of fuzzy linguistic rules. These rules will produce an approximate decision in the same manner as a human does. The block diagram of a fuzzy control system is shown in Fig. 4. A fuzzy controller is composed of four elements [9]-[12]:

1- A rule-base:
   It is a set of If-Then rules which contains a fuzzy logic quantification of the expert’s linguistic description of how to achieve good control.

2- An inference mechanism:
   Also called an “inference engine” or “fuzzy inference module”, it emulates the expert’s decision-making, interpreting and applying knowledge as in how to control the plant well.

3- A fuzzification interface:
   It converts the controller inputs into information the inference mechanism can easily use to activate and apply the rules.

4- A defuzzification interface:
   It converts the conclusions of the inference mechanism into actual inputs for the process.
The first modification concerns the choice of the membership functions for the inputs and the outputs of the system. For the inputs of the controller crisp, adjacent, semi-closed membership functions are used; they are distributed throughout the discourse universe. Since the membership degree for the crisp sets takes only two values 0 or 1 which is very simple to determine, the necessary computing time at this stage in the case of fuzzy controller for both fuzzification and inference operations is extremely minimized. Furthermore, there will be no need to infer the rules, because only one rule from the rule-base is active. Once the membership functions of the input variables are known, the fired rule is easily determined and the corresponding output singleton is defined. At this stage, the decision making time is considerably reduced because the defuzzification step is wholly avoided.

The second modification is related to the computation of the output. The main aim at this stage is to smooth the brief transitions caused by the choice of the crisp membership functions. Firstly, the amount by which the input variables are shifted with respect to the centers of their respective crisp membership functions is calculated. The controller is illustrated in Fig. 5, where the input variables are \( T_H/T_V \) and \( dT_H/dT_V \) defining the error and the error variation respectively. The gradual output control value is computed according to equation (2).

\[
y_H = Rule(i, j) - \frac{(\Delta T_H + \Delta dT_H)}{2}
\]

\[
y_V = Rule(i, j) - \frac{(\Delta T_V + \Delta dT_V)}{2}
\]

Whereat:
- \( i \) is the number of the crisp set which belongs to the error variables \( T_H/T_V \)
- \( j \) is the number of the crisp set which belongs to the variation of errors \( dT_H/dT_V \)

\( \Delta T_H/\Delta T_V \) is the difference between the error values \( T_H/T_V \) and the center of their membership sets.

\[
\Delta T_H = T(i) - T_H
\]

\[
\Delta T_V = T(i) - T_V
\]

\( T(i) \) is the center of the set number \( i \), for \( T_H \) and \( T_V \) respectively.

\( \Delta dT_H/\Delta dT_V \) is the difference between the error derivatives and the center of their membership sets.

\[
\Delta dT_H = T(j) - dT_H
\]

\[
\Delta dT_V = T(j) - dT_V
\]

\( T(j) \) is the number of the crisp set that belongs to the variation of the error variables \( dT_H/dT_V \).

Rule \((i, j)\) is the singleton containing the cell \((i, j)\) in the rule base.

As shown in Fig. 5, the controller consists of three main blocks. The membership determination block provides indices \( i, j \) of the sets which belongs to the error and the error derivative \( T_H/T_V \) and \( dT_H/dT_V \) respectively. Instead of the defuzzification and the inference mechanism involved in the fuzzy controller, the output computation block incorporates simple arithmetic operations to compute the real controller output. The steps given below illustrate the procedure of output computing.

**Step 1:** Compute \( \Delta T_H/\Delta T_V \), the difference between the center of the \( i \)-th set and the error value.

**Step 2:** Compute \( \Delta dT_H/\Delta dT_V \), the difference between the center of the \( j \)-th set and the error derivative.

**Step 3:** Extract the contents of the cell \((i, j)\) in the rule table which represent the output singleton.

**Step 4:** Adjust the singleton value by subtracting the mean of \( \Delta T_H/\Delta T_V \) and \( \Delta dT_H/\Delta dT_V \).

Consequently, the computed value is a crisp (real) one, and does not need to be converted (defuzzified). This method simplifies all the steps involved in fuzzy reasoning, and minimizes the computation time. Thus, the time required for decision making will be very short. Clearly, not only will the implementation of such a controller for real time application be much easier than that of a fuzzy controller, but also no special hardware resources will be necessary.

### III. Results of the experiment

In order to analyze the operation accuracy of the designed and implemented controlling system, a 10-cm indicator was installed on the surface of the solar cell. If the controlling system operates accurately, the solar cells will be perpendicular to the sunlight and, as a result, the indicator will not cast any shadow. The errors in the operation of the controlling system are directly related to the length of the produced shadow.

Fig. 6 shows sample shadow lengths produced by the indicator on a day in June recorded hourly. As indicated in Fig. 6, due to the high intensity of the sunlight at midday, the tracking system has the least amount of error. These operational errors increase, however, as the sun begins to set. The reason for this kind of operation can be accounted for by the light dispersed in the environment which acts as noise for the mentioned system, and also by the low intensity of the sunlight during this time. In other words, the ratio of signal/noise (S/N) is significantly decreased.
IV. Conclusions

This paper presents a controlling system implemented on solar power cells which are based on a fuzzy algorithm. ATMega32 microcontroller utilized in the implemented system is expeditious in control and enjoys a small size in comparison with conventional communication systems. The controlling system for the sunlight-tracking power plant uses voltages generated by cells. This reliable system is able to stabilize the maximum power transfer at all operating times, and can be incorporated in large installations.

References


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