12th International Conference on DEVELOPMENT AND APPLICATION SYSTEMS, Suceava, Romania,

Fuzzy Decision Support System for Solar Tracking Optimization

Iulia Stamatescu, Grigore Stamatescu, Nicoleta Arghira, Ioana Făgără□an and Sergiu Stelian Iliescu
Department of Automatic Control and Industrial Informatics
University "Politehnica" of Bucharest
Bucharest, Romania
iulia.dumitru@aii.pub.ro

Abstract—**This paper presents the design and implementation of a fuzzy decision support system for control of photovoltaic panel movement in order to improve the availability of solar energy and the system's total efficiency. The designed algorithm is implemented on a solar tracking experimental platform using a fuzzy logic control strategy. It makes use of measured values for radiation from appropriate sensors and assures command of the platform's two positioning motors. The solution was developed as a virtual instrument, using a graphical programming environment. This allows for fast deployment, versatility and scalability.**

Keywords—solar energy; solar tracking system; fuzzy control; renewable energy, motor, sensor

I. INTRODUCTION

Increasing energy demand, steady depletion of the existing sources of fossil fuels and increasing concern about environmental pollution pushed researchers to explore new technologies for the production of electricity from clean sources, renewable such as solar and wind [1], [2]. Solar energy is the oldest primary source of energy. It is a source of clean, renewable energy and it is found in abundance in every part of the world. Solar energy can be converted into mechanical energy or electricity with adequate efficiency.

Information about the quality and amount of solar energy available at a specific location is of prime importance for the development of a solar energy system. However, the amount of electricity obtained is directly proportional to the intensity of sunlight falling on the photovoltaic panel. To extract a larger amount of solar energy, the efficiency of photovoltaic systems (PV) has been studied by a large number of scientists and engineers. In general, there are three ways to increase the efficiency of photovoltaic systems. The first method is to increase the efficiency of power generation of the solar cells, the second is related to the efficiency of the control algorithms for energy conversion, and the third approach is to adopt a tracking system to achieve maximum solar energy at any given time during the day.

The interest in photovoltaic tracking systems as a new method for studying and teaching increased in the past years. A wide number of papers describe a consistent number of photovoltaic panel solar tracker applications and their area of employment. In [3] a single-axis sun-tracking system with two sensors was designed. The data acquisition, control and monitor of the mechanical movement of the photovoltaic module were implemented based on a programmable logic controlling unit. The authors of [4] present the design and construction of a two axis solar tracking system in order to track the photovoltaic solar panel according to the direction of beam propagation of solar radiation.

To achieve maximum solar energy, solar power systems generally are equipped with functions that implement the maximum power point tracking (MPPT) as shown in [5]. The maximum point is a unique point on the power-voltage (P-V) curve where the photovoltaic system produces the maximum power. Although there are many factors influencing the energy conversion efficiency, the maximum power point tracking is the most vital aspect of control design for photovoltaic generation. The nonlinearity of the MPPT control problem is due to the non-linear nature of the PV and the continuous changes of its parameters due to the variations of the environmental conditions [6]. A significant number of MPPT algorithms have been presented in the literature such as [7] and [8].

In industrial automation applications, for continuous control, PID-type controllers where often employed [9] until, in 1974, the first fuzzy control application appeared [10]. Since then, fuzzy logic control (FLC) has been increasingly preferred as a method of designing controllers for dynamic systems, even where traditional methods cannot be used [11]. Fuzzy logic control seems to be appropriate when working with a certain level of imprecision, uncertainty and partial knowledge and also in cases where the knowledge of operating with the process can be translated into a control stately that improves the results reached by other classical strategies [12].

Our work enhances previous related developments such as [13] through design and modeling of a fuzzy logic controller. The paper presents a solar tracking method for control of photovoltaic panel movement in order to improve the conversion efficiency of the system. The presented system and algorithm have the following advantages: the photovoltaic panel physical model is a didactic system and the programming environment in which it is developed the presented algorithm allows designers faster and easier development of block diagrams for any type of data acquisition, analysis, and control application. This implementation technique reduces the costs of tracking method and makes it a cost-effective technology.

The rest of the paper is structured as follows. Section 2 describes in detail the hardware structure of the solar tracking experimental platform and its characteristics. Section 3 is dedicated to the theoretical design of the fuzzy logic controller. Section 4 presents the implementation details as a virtual instrumentation system and experimental results obtained by using the proposed algorithm. Section 5 concludes the paper and draws the main directions for future work.

II. EQUIPMENT DESCRIPTION

In order to implement a tracking algorithm, solar panels have to be placed on a structure that allows moving (rotating) of the panel on one or preferably two axis. In addition, the structure with one or two degrees of freedom must dispose of actuators for effective movement.

The equipment used in the experiments is a didactic miniature equipment produced by Fischer Technik, type Solat Tracking 2-Axis 24V with 24-pin interface, This is equipped with a set of three photovoltaic cells that are placed on the same plane, in series, in the upper bar assembly. The frame on which the solar cells are mounted includes two motor-powered from direct current (DC) supplied at a constant 24 voltage and which allows the positioning on two axes of rotation. The allowed movements of the solar panels on the mechanical structure are the horizontal direction, azimuth angle, and the angle of inclination, elevation angle. It appears that the azimuth angle variation is wider compared to the time of day and the elevation variation is relative to the time of year (season). This behavior is due to the trajectory of the sun throughout the day, depending on the season.

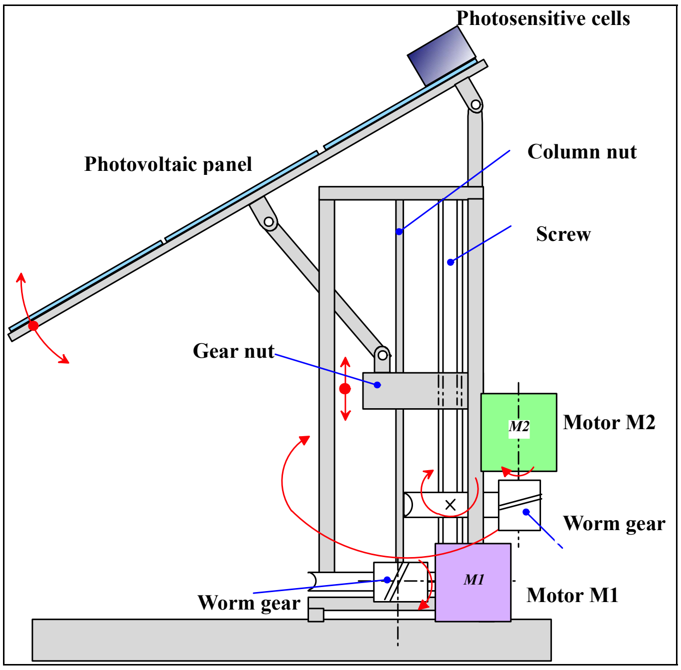

Fig. 1. The mechanical structure for the positioning of the solar panels.

Figure 1 shows schematically the basic structure of the equipment described above. In addition, in order to determine the maximum light intensity on the underlying photovoltaic cells panel, four photosensitive cells can be found; two on each direction, on the neighboring sides of the panel and perpendicular to it. The photosensitive cells, detect light intensity from eastern, western, southern, and northern directions, respectively – see Figure 2).

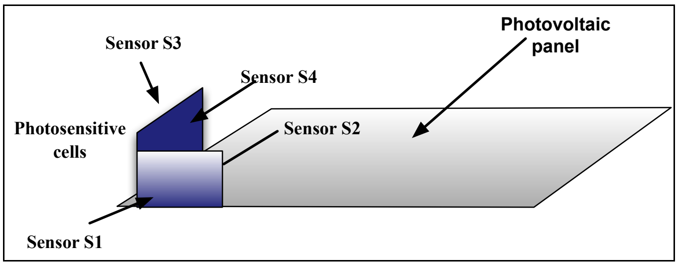

Fig. 2. The sensitive elements mounted perpendicular to the panel surface.

III. BACKGROUND OF THE FUZZY CONTROLLER

For control design, the system behavior has to be known. For that, usually a description of the system by mathematical modeling is done. Very often, it is passed to a physical analysis of the system in order to obtain the differential and algebraic equations at first. The second step is to determine the system inputs and outputs, to describe a mathematical model from the system equations and, if needed, to linearize it. Then, it can be measured the system parameters and write down the complete model with numerical values.

When the model of the system is determined, a controller can be designed. Depending on the performances that the system should achieve (e.g. stability of the system and quality of the system behavior, optimal behavior of the system according to a criterion, etc.) there are many ways to design and implement a controller.

Another method to develop a controller is using the fuzzy logic control sets also known as fuzzy aggregates instead of the numbers for the arithmetic for the fuzzy theory. Fuzzy logic control (FLC) provides a conceptual base for practical problems where the process variables are represented as a linguistic variables which can only present a certain limited number of possible values and then be processed using a series of rules [12].

The following overview provides the advantages and disadvantages of fuzzy control [14]:

- Simple implementation of verbally expressed rules (if ..., then...) on a computer to solve a problem.
- The behavior of the fuzzy system is understandable to human beings.
- Avoids the costly development of a mathematical description when compared with conventional methods.
- Possible to use for processing complicated and evolved processes.

- Task definitions with not enough knowledge of the system and little or very imprecise knowledge of the system behavior results in bad, possibly unusable fuzzy solutions.
- Usually no adaptability and learning capability if the system behavior changes.
- Design of a system requires experience because of the many degrees of freedom.

The following figure (Figure 3) illustrates the components of the fuzzy controller and its functional principle. Fuzzy control is based on a collection of rules, known as the rule base.

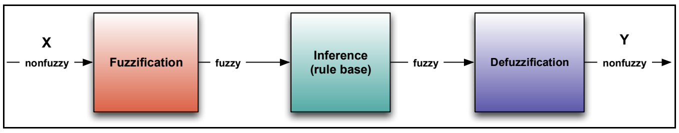

Fig. 3. Fuzzy decision process.

The functional principle is divided into the following steps:

- Fuzzification - The degrees of fulfillment for the linguistic values (degrees of membership of the fuzzy sets) of the linguistic variables are assigned to the non-fuzzy input values.
- Inference or Rule Based Fuzzy Control Algorithm – For each rule of the rule base, the degree of fulfillment of the THEN part is formed from the degree of fulfillment of the IF part by a certain method. This process is also called implication. The degree of fulfillment of the THEN part is equivalent to the degree of fulfillment of the rule, which is also called the rule intensity. All these individual rule evaluations put together result in one membership function for the output signal, which is also termed composition. The resulting membership function describes a ”fuzzy control command”. When the IF part contains a combined statement ”IF.... AND...” — (THEN....), the fuzzy logic AND operation is executed first and the degree of fulfillment is used in the overall rule evaluation. All these statements together are often called aggregation.
- Defuzzification - The most representative numeric (nonfuzzy) output value is calculated for the control variable from the fuzzy control command (in the form of the resulting membership function). The set of conditions belongs to the input domain and the set of consequences to the output domain [12]. The fact that various rules can be used simultaneously is due to the conversion of values obtained from the sensors to linguistic terms, assigning a membership function, mA, to each one. If triangular partition rule base are used [15], the input and the output are subdivided using triangular membership function of the form:

The set of conditions belongs to the input domain and the set of consequences to the output domain [12]. The fact that various rules can be used simultaneously is due to the conversion of values obtained from the sensors to linguistic terms, assigning a membership function, mA, to each one. If triangular partition rule base are used [15], the input and the output are subdivided using triangular membership function of the form:

$$\mu_{A_i}(x) = \begin{cases} (x-a_{i-1})/(a_i-a_{i-1}) & if \quad a_{i-1} \le x \le a_i \\ (-x-a_{i+1})/(a_{i+1}-a_i) & if \quad a_i \le x \le a_{i+1} \\ 0 & otherwise \end{cases} \quad .1$$

IV. Fuzzy Decision Suport System Implementation And Experimental Results

The fuzzy decision support algorithm implemented is using the control scheme depicted above (Figure 4). The chosen approach used to implement the fuzzy controller is a Mamdani system which offers which is not so computationally efficient and less suited to numeric optimization than Takagi-Sugeno systems, but it is widely employed and operates with intuitive concepts. The system inputs are the maximal solar intensity on eastward-westward direction, *e1*, and northward-southward direction, *e2,* and their variation with the time, $\frac{de_1}{dt}$ and $\frac{de_2}{dt}$. The output of the system is a pulse which controls the motors movements.

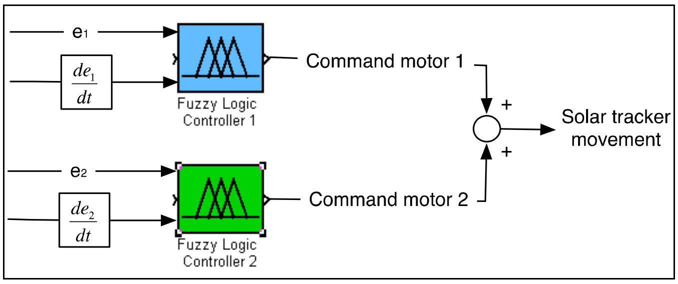

Fig. 4. Direct fuzzy logic control algorithm.

At first the algorithm reads the solar radiation using the four photosensitive cells. The four sensors are separated as two groups. One is using two photosensitive cells to represent the eastward-westward direction sensor and the other one is using the last two photosensitive cells to represent the northward-southward direction sensor. The data acquisition equipment, NI-DAQ 6009, reads the different output voltages of the sensor and deliveries it to the fuzzy controller. Then, the fuzzy controller produces pulses to motor drivers and the motor drivers produce PWM signals to control step motors for tuning desired angles. Control problems are reduced because the two motors are decoupled, i.e., the rotation angle of one motor does not influence the elevation angle of the other motor.

In the implementation of the fuzzy logic controller, the triangular decomposition of the inputs has been chosen. The extremes of the input universes of discourse, corresponding to e and de $\frac{de}{dt} = \Delta e$ are [-4, 4]. Those of the output have been chosen to be [-1, 1] with centers [±1; ±0:8; ±0:6; ±0:4; ±0:2; 0].

These values were chosen based on previous knowledge of the system dynamics.

In this case, two-input single-output system, the rules take the form: *"**if** the error is positive large **and** the variation in error is negative small **then** make the control signal change positive large"*. The rule base for the fuzzy algorithm is presented in table I. Terms extra-large, EL, large, L, medium, M, small, S, extra-small, ES and zero, Z, are used to describe the fuzzy variables and the control action [12].

TABLE I. THE FUZZY CONTROL RULES USED

Δe \ e	-L	-M	-S	Z	+S	+M	+L
-L	-EL	-EL	-L	-M	-S	+L	+EL
-M	-EL	-L	-M	-S	Z	+M	+EL
-S	-L	-M	-S	-ES	+ES	+S	+M
Z	-M	-S	-ES	Z	+ES	+S	+M
+S	-L	-M	-ES	+ES	+S	+M	+L
+M	-EL	-L	Z	+S	+M	+L	+EL
+L	-EL	-L	+S	+M	+L	+EL	+EL

The algebraic product operator is used as the conjunction operator, each rule recommends a control action, Dui; j, with a membership function $\mu_{\Delta u_{i,j}} = \mu_{e_i}\mu_{\Delta e_i}$, where μ_{e_i} and $\mu_{\Delta e_i}$ are calculated with 1. The methodology used in deciding what control action should be taken results in firing of four rules. The combination of these rules produces a non-fuzzy control action, Δu, which is calculated using the weighted averaging defuzzification method, as mentioned before. The resulting control action can be calculated by:

$$\Delta u = \frac{\sum_i^{i+1}\sum_j^{j+1}(\mu_{\Delta u_{i,j}}\Delta u_{i,j})}{\sum_i^{i+1}\sum_j^{j+1}\mu_{\Delta u_{i,j}}} \quad .2$$

and, as in this case $\sum_i^{i+1}\sum_j^{j+1}\mu_{\Delta u_{i,j}} = 1$, results .3

$$\Delta u = \sum_i^{i+1}\sum_j^{j+1}(\mu_{\Delta u_{i,j}}\Delta u_{i,j}) \quad .4$$

The implementation of the control algorithm is numerically carried out through a specialized device and computing program capable to acquire analog and digital input, to make a series of preliminary data processing, to take a set of decisions about the way the process should be influenced and to update the output signals according with the set the decisions taken. Because now it is easier to interface with real-world signals, analyze data for meaningful information, and share results the LabVIEW environment was chosen for the implementation of the control algorithm [16] and [17].

The presented fuzzy control algorithm has some advantages such as reducing consumption power of step motors and achievement of fast and smooth fixed positioning. Because the speed rotation of the sun is very slow, therefore, the fuzzy control algorithm has enough ability to complete this goal.

V. CONCLUSIONS

This paper presents a solar tracking method design and implementation for experimental sun follower platforms. The presented control algorithm commands the movement of a photovoltaic module in order to follow the suns radiation and to maximize the obtained solar energy. The programming environment in which the presented, fuzzy logic control, algorithm is developed allows designers faster and easier development of block diagrams for any type of data acquisition, analysis, and control application. This implementation technique reduces the costs of tracking method and makes it a cost-effective technology.

Regarding future work, this will follow two main directions. First, extensive experimental evaluation has to be carried out in order to validate our approach. Second, a comparison between different control strategies in similar operating scenarios will lead to choosing the best solution depending on the situation.

ACKNOWLEDGMENT

The support of the Romanian Executive Agency for Higher Education, Research, Development and Innovation Funding (UEFISCDI) through the project "Intelligent Decision Support System applied to Low Voltage Electric Networks with Distributed Power Generation from Renewable Energy Sources" (InDeSEN) of the "Partnerships in Priority Sectors" funding program 2012, competition PN-II-PT-PCCA-2011-3, is gratefully acknowledged.

REFERENCES

[1] F. Dragomir, S. Iliescu, O. Dragomir, and E. Minca, "Pv grid connected system with fuzzy intelligent control," *The 10th International Conference on Engineering of Modern Electric Systems, Oradea, Romania*, vol. 2, no. 1, pp. 97–101, 2009.

[2] O. Dragomir, F. Dragomir, and V. Stefan, "Guideline to choose a forecasting tool with fuzzy logic support," *8th IEEE Conference on Industrial Electronics and Applications (ICIEA),* pp. 595 – 600, 19-21 June 2013.

[3] A. Al-Mohamad, "Efficiency improvements of photo-voltaic panels using a sun-tracking system," *Applied Energy,* vol. 79, pp. 345–354, 2004.

[4] R. B. M. R. I. Sarker, Md. Riaz Pervez, "Design, fabrication and experimental study of a novel two-axis sun tracker," *International Journal of Mechanical & Mechatronics Engineering,* vol. 10, no. 1, 2010.

[5] Y.-C. Wu, M.-J. Chen, S.-H. Huang, M.-T. Tsai, and C.-H. Li, "Maximum power point tracking on stand-alone solar power system: Threepoint - weighting method incorporating mid-point tracking,"

International Journal of Electrical Power & Energy Systems, vol. 52, no. 0, pp. 14 – 24, 2013.

[6] A. I. Dounis, P. Kofinas, C. Alafodimos, and D. Tseles, "Adaptive fuzzy gain scheduling pid controller for maximum power point tracking of photovoltaic system," *Renewable Energy,* vol. 60, no. 0, pp. 202 – 214, 2013.

[7] M. M. Algazar, H. AL-monier, H. A. EL-halim, and M. E. E. K. Salem, "Maximum power point tracking using fuzzy logic control," *International Journal of Electrical Power & Energy Systems,* vol. 39, no. 1, pp. 21 – 28, 2012.

[8] A. Daoud and A. Midoun, "A fuzzy logic based photovoltaic maximum power tracker controller," *Proceedings of the 4th International Multiconference on Computer Science and Information Technology/CSIT2006,* Editor G. Issa, E. Qaddoura, E. Al-Qawasmeh, and G. Raho, Eds., 2006.

[9] S. T. H.-X. Li, "A fuzzy plc with gain-scheduling control resolution for a thermal process - a case study," *Control Engineering Practice* 7, vol. 7, no. 4, pp. 523–529, 1999.

[10] E. Mamdani, "Applications of fuzzy algorithms for simple dynamic plant," *Proceedings of the Institution of Electrical Engineers*, vol. 121, no. 1585-1588, 1974.

[11] ——, "Twenty years of fuzzy control: experiences gained and lessons learnt," *Second IEEE International Conference on Fuzzy Systems*, vol. 1, no. 339 - 344, 1993.

[12] E. F. Camacho, M. Berenguel, F. R. Rubio and D. Martinez, *Control of Solar Energy Systems, ser. Advances in Industrial Control. Springer London,* 2012, no. Print ISBN 978-0-85729-915-4.

[13] Y. J. Huang, I. B. C. Wu, C. Y. Chen, C. H. Chang, and I. T. C. Kuo, Member, "Solar tracking fuzzy control system design using FPGA," *Proceedings of the World Congress on Engineering* 2009, vol. 1, 2009.

[14] Siemens, "Fuzzy control++," Siemens, Tech. Rep., 2003.

[15] T. Sudkamp and H. R. II, "Interpolation, completion, and learning fuzzy rules," *IEEE Trans. Syst. Man Cybern*, vol. 24, pp. 332–342, 1994.

[16] S. Josifovska, "The father of labview," *IEE Rev*, vol. 49, no. 9, pp. 30–33, 2003, p.30-33.

[17] K. N and G. C, "Dsp system design using labview and simulink: a comparative evaluation," *Proceedings of IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP),* Toulouse, France, vol. 2, 14–19 May 2006.