Advances in Engineering Research, volume 213
Proceedings of the International Scientific and Practical Conference "Young Engineers of the Fuel and Energy Complex: Developing the Energy Agenda of the Future" (EAF 2021)

Fuzzy Logic Application in Solar Panels

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ABSTRACT
The possibility of using fuzzy logic in solar panels, which are a complex technical system, is being considered. Fuzzy logic allows you to easily and efficiently configure the controller in a nonlinear solar panel control system, ensuring its reliable operation by changing parameters, load and supply voltage.

Keywords: *Solar panel, Fuzzy logic, Tracking system, Stepper motor.*

1. INTRODUCTION

1.1. Literature review

At the present stage, solar energy has been widely developed, since solar energy is environmentally friendly and resource-intensive. Modern solar panels are complex technical systems with undefined parameters. Their efficiency depends on the intensity of the solar flux falling on the panel; panel temperature; seasons of the year; weather conditions and the relative position of the panels and the sun.

In work [1, 2], the influence of the intensity of solar radiation and ambient temperature is considered. For optimal energy conversion, a design of a uniaxial or two-axis tracking system is proposed, the control of which is realized on the basis of a DC motor.

Work [3] presents the design of a tracking system using a servo system, which consists of a sunlight transmission unit, a fuzzy logic unit, an output drive control unit, a comparison and adjustment unit.

In work [4], the tracking system is controlled using fuzzy logic with three membership functions. Controlled variables are the pitch angle and the yaw angle in the active biaxial solar tracking system. Fuzzy logic control is an error at the input and a pulse width modulator at the output.

In work [5], a comparative analysis of the use of a PID regulator and fuzzy logic in a tracking system of uniaxial structure is considered.

1.2. Description of the object

This work discusses the design of a two-axial tracking system using stepper motors.

In Figure 1 shows a diagram of the panel tracking system, here M1 and M2 are stepper motors; P1 and P2 – gearbox; a photoresistor is used as a sensor. Electromechanical devices allow you to change the azimuth angle and the angle of elevation.

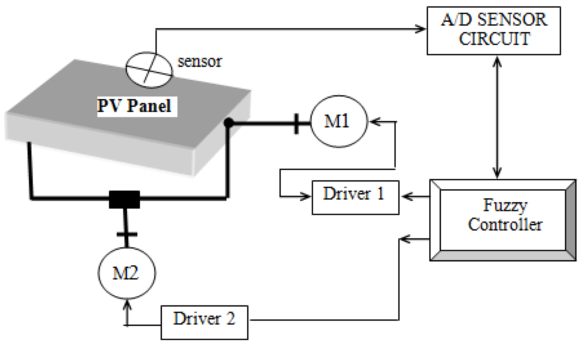

Figure 1 Diagram of the panel tracking system.

There is a single maximum power point (MPP) corresponding to a specific voltage and current (Figure 2).

By varying the temperature of the maximum power point (MPPT) tracking mechanism, the new changed maximum power point on the corresponding curve is tracked. MPPT allows you to extract maximum power from a solar PV module and transfer it to a load. AC /

DC converter acts as an interface between the load and the module.

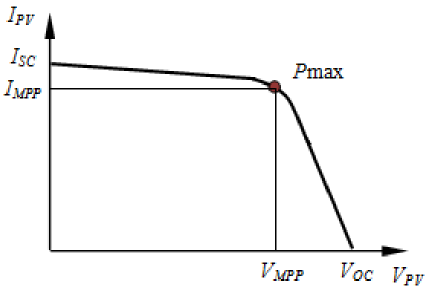

Figure 2 Current-voltage characteristic of the photovoltaic module.

The MPPT modifies the duty cycle to keep the transmit power from the solar PV module to the load at its maximum level.

2. MATHEMATICAL MODEL OF THE OBJECT

The solar panel tracking system is a complex system, for which there is no exact mathematical description. We will decompose the system into subsystems, writing their ratios in the form:

$$S = \{X, R\} \tag{1}$$

where $X = \{x_1, x_2, \ldots, x_n\}$ is subset of system elements x_i, R is the regularity of the tracking system, taking into account the order of the elements x_i and their interdependence, interdependence of external conditions and subset X.

For the analysis of the tracking system, one cannot ignore the vector $\mathbf{Y} = \{y_1, y_2, \ldots, y_m\}$, which is an output quantity represented in terms of {input-output}. With known sets X and R, the membership function will be written as:

$$f : \{X, R\} \xrightarrow{u_i} \mathbf{Y} \tag{2}$$

where u_i is a universal set that includes the control action in the subsystem [6].

Let's set the control action on the tracking system in the form of linguistic rules, controlling the information about the position of the tracking system at each moment of time, which depends on the temperature. Then we write down the linguistic terms of temperature, defining them as: cold, cool, normal, warm, hot. Based on the syntactic rules of IF-THEN, introduced into the fuzzy controller, at the output of which only one value of the control action U will be obtained [7].

The mathematical description of the logical controller and the control object written using fuzzy production rules will take the following form:

$$\begin{aligned}
&\Pi_{r_1} : \text{if } x_1^1, \text{ have } A_{r_1 1} \text{ and if } x_1^2 \text{ and} \ldots \text{ and,}\\
&\text{have } A_{r_1 2} \text{ and if } x_1^2, \text{ have } A_{r_1 2} \text{ and} \ldots \text{ and}\\
&\text{if } x_1^{n1}, \text{have } A_{r_1 n1}, \text{have } \vec{u}(t) = L_{\text{к}r_1}\left(\vec{e}(t)\right);\\
&\Pi_{r_2} : \text{if } x_2^1, \text{ have } B_{r_2 1} \text{ and if } x_2^2, \text{ have } B_{r_2 2}\\
&\text{and} \ldots \text{ and if } x_2^{n2}, \text{ have } B_{r_2 n2},\\
&\text{have } \vec{y}(t) = L_{\text{оу}r_2}\left(\vec{u}(t)\right),
\end{aligned} \tag{3}$$

where n_1 and n_2 are the dimensions of the vectors $\vec{x}_1$ and $\vec{x}_2$ respectively; $r_1 = 1, 2, \ldots, m_1$ is Fuzzy production rules; $L_{\text{к}r_1}(\cdot)$, $L_{\text{оу}r_2}(\cdot)$ are linear membership functions.

We write the mathematical model of the electrical drive, the output parameter of which is the speed, in the form of the Sugeno fuzzy inference algorithm:

$$\vec{u}(t) = \frac{\sum_{r_1=1}^{m_1} \mu_{r_1}^A(\vec{x}_1) \cdot L_{\text{к}r_1}\left(\vec{e}(t)\right)}{\sum_{r_1=1}^{m_1} \mu_{r_1}^A(\vec{x}_1)} \tag{4}$$

$$\vec{y}(t) = \frac{\sum_{r_2=1}^{m_2} \mu_{r_2}^B(\vec{x}_2) \cdot L_{\text{оу}r_2}\left(\vec{u}(t)\right)}{\sum_{r_2=1}^{m_2} \mu_{r_2}^B(\vec{x}_2)}, \tag{5}$$

where $\mu_{r_1}^A(\vec{x}_1)$, $\mu_{r_2}^B(\vec{x}_2)$ are membership functions n_1-dimensional and n_2-dimensional fuzzy sets $A_{r_1 1} \cap A_{r_1 2} \cap \ldots \cap A_{r_1 n_1}$ and $B_{r_2 1} \cap B_{r_2 2} \cap \cap \ldots \cap B_{r_2 n_2}$ respectively.

The mathematical description of the tracking system can be represented in the form of nonlinear difference equations of the l-th order:

$$y_i = f\left(y_{i-1}, \ldots, y_{i-l}, u_i, u_{i-1}, \ldots, u_{i-l_1}\right), \tag{6}$$

where $f(\cdot)$ is a function that is continuous and has a restriction on $R^n \ (n = l + l_1 + 1)$ by a nonlinear function.

We write the dynamics of the fuzzy complex model in the form of a set of fuzzy production rules:

$$\Pi_r : \text{if } x'_{1i}, \text{ have } A_{r_1} \text{ and } x'_{2i}, \text{ have } A_{r_2}$$

$$\text{and } \ldots \text{and } x'_{l_2 i}, \text{ have } A_{r_{l_2}}, \text{ have}$$

$$y_i = \sum_{j=1}^{l} p_{rj} y_{i-j} + \sum_{j=l+11}^{l+l_1} p_{rj} u_{i-j+(l+1)}, \quad (7)$$

where $\vec{x}' = (x'_1, x'_2, \ldots, x'_{l_2})$; A_{rj} are given fuzzy numbers; A_{rl} are set parameters.

To implement adaptive control, an information-measuring system is included in the MPPT structure, which allows obtaining information about the temperature and intensity of sunlight. The problem of adaptive control is reduced to the search for the $Q\pi \in |\pi(t)| \le c\pi$ control function at $t > t_0$, which satisfying the conditions:

$$\begin{cases} x_i(t) = F[x(t), u(t), \xi] + \boldsymbol{\pi}(t); \\ u(t) \in Q_u,\ x(t) \in Q_x,\ t \in \{t_0, t_T\} \end{cases} \quad (8)$$

where x_i is a some value of the position in the state space $\{x_0, x_1, \ldots, x_T\}$; $x(t)$ is a tracking mechanism state; ξ is a tracker parameter vector; $\boldsymbol{\pi}(t)$ is a vector of external disturbing influences, including kinematic, force and information; Q_u, Q_x, Q_π are a sets of states, which include variables; $c\pi$ are a maximum disturbance values; t_T, t_0, t are a time values corresponding to the current, start and end.

The control function is optimal when the equality will be fulfilled:

$$F[u_i(t)] = ext\{F[u(t)]\} \text{ or}$$

$$X[x_i(t)] = ext\{F[x(t)]\}, \quad (9)$$

where F is a functional corresponding to optimal control; X is a functional corresponding to motion to a given point.

The motion of the tracking mechanism is interconnected with a certain prior environment. Regardless of the geometry of the environment, the state of the MPPT is determined by the *x* variable in absolute coordinates.

Consider the fuzzy state variable of the tracking system:

$$s \in S = \{s_i,\ i = 1 : \mathrm{m}\}, \quad (10)$$

which at the moment of time $t = kT$ is denoted as $s = s^k$, and which is a fuzzy relation *Y* with the variable $y = [y^1, y^2, y^3, y^4]$, written as a membership function of the form:

$$\mu_{s_1}(y) \min \begin{Bmatrix} \mu_{\mathrm{CM}}(y^1),\ \mu_{\mathrm{LG}}(y^2), \\ \mu_{\mathrm{MD}}(y^3),\ \mu_{\mathrm{LG}}(y^4) \end{Bmatrix} \quad (11)$$

The command used before the deactivation stage represents a set of the fuzzy subsets $U^i,\ i = 1:2$, where $\mu_{U^i}(u^i)$ is a membership function.

Consider two commands:

- temperature u^1;
- intensity of solar flux u^2.

Let us write two fuzzy subsets in the form of a vector $\mathbf{U} = [U^1, U^2]^T$ with variable $u = [u^1, u^2]^T$. At the moment of time $t = kT$, a command is used in a fuzzy controller of the type $U^k = [U^{1k}, U^{2k}]^T$.

Let **U** be the set of all fuzzy vectors that are inputs generated by the logic controller. Each change in the position of the tracking system, which is tracked by the fuzzy controller, is a fuzzy dynamic system, written in the form of linguistic terms:

$$s^{k+1} = f(s^k, U^k), \quad (12)$$

where the transition function f can be written as:

$$f : S \times U \to S. \quad (13)$$

The tracking system can be written in the form of a fuzzy mathematical model in the form of a set of rules that include knowledge about the temperature and intensity of the solar flow. Let us approximate the space *U* in the form of a finite space of the corresponding fuzzy U^j commands:

$$U = \{U^j,\ j = 1 : \mathrm{p}\}, \quad (14)$$

where U^j is one of the possible values of the vector of a fuzzy variable $U = \left[U^1, U^2\right]^T$, the membership function of which is a vector of two functions:

$$\mu_U(u) = \left[\mu_{U^1}\left(u^1\right), \mu_{U^2}\left(u^2\right)\right]^T. \quad (15)$$

Let's write down the linguistic meanings as "TS" = "cold"; "TN" = "normal;" "TW" = "warm"; "TH" = "hot" as shown in Figure 3.

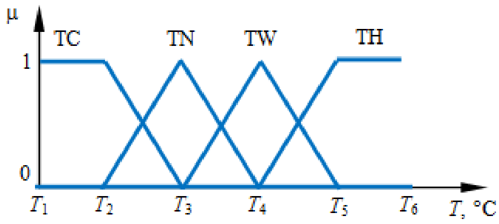

Figure 3 Linguistic variable – temperature.

Since the fuzzy values of s^i, U^j are fuzzy sets, including the variables *y* and *u*, respectively, the commands can be represented as:

$$C: Y \times U \to [0, 1], \quad (16)$$

$$\mu_c(y, u) = \sup\left\{ \begin{matrix} \mu_Q\left(s^i, U^j\right) \wedge \mu_{s^i}(y) \wedge \\ \wedge\, \mu U(u) \end{matrix} \right\} \quad (17)$$

$$s^i \in S,\ U^j \in U. \quad (18)$$

To implement the solar panel, it is necessary to provide a mathematical description of the stepper motor.

When choosing a stepper motor (SM) and a control system for its phases, it is necessary to take into account the dependence of the torque on the speed. Motor windings are inductors that determine the rise and fall times of the current. Therefore, in the mathematical model, we will take into account that if a rectangular voltage is applied to the winding, then the current will not be rectangular.

The windings are powered from a constant voltage source.

In accordance with the works [8, 9], we write the mathematical description in the form of a system of equations:

$$\begin{cases} \dfrac{di_{sa}}{dt} = \dfrac{1}{L_{sa}}\begin{pmatrix} u_{sa} - r_{sa} \cdot i_{sa} - Kr \cdot T \cdot \cos(\beta) + \\ +T \cdot i_{ra} \cdot \sin(\beta) \cdot w_r \end{pmatrix} \\ \dfrac{di_{sb}}{dt} = \dfrac{1}{L_{sb}}\begin{pmatrix} u_{sb} - r_{sb} \cdot i_{sb} - Kr \cdot T \cdot \sin(\beta) + \\ +T \cdot i_{ra} \cdot \cos(\beta) \cdot w_r \end{pmatrix} \\ \dfrac{di_{ra}}{dt} = Kr \\ \dfrac{d\beta}{dt} = w_r \\ \dfrac{dw_r}{dt} = \dfrac{p}{J}\left(T_e - T_c - k \cdot w_r\right) \end{cases} \quad (19)$$

where i_{sa}, i_{sb}, i_{ra} are a currents in the stator and rotor windings; U_{sa}, U_{sb}, U_{ra} are a voltages on the stator and rotor windings; r_{sa}, r_{sb}, r_{ra} are an active resistances of the phases of the stator and rotor windings; L_{sa}, L_{sb}, $L_{ra} = L_{r0} + L_{r1} \cdot \cos(4\beta)$ are a phase inductance of the stator and rotor windings; T – mutual inductance; β – angular position of the rotor; w_r – angular velocity; T_L – torque of load; *Te* – electromagnetic torque; *J* is a moment of inertia of the rotor; *p* is a number of poles.

The mechanical characteristic of a stepper motor has two zones that adversely affect its operation: resonance and hysteresis, and its control is carried out using a driver, therefore, to improve the quality of transient processes in the system of equations (19), it is necessary to take into account conditions (20) in each winding:

$$\begin{cases} \text{if } ga(t) = 1 \text{ have } u_{sa} = U; r_{sa} = r + 2R_{ON}; \\ \text{if } ga(t) = 0 \text{ and } ga(t-h) = 1 \\ \text{have} \begin{cases} \text{if } i_{sa} > 0 \text{ have } u_{sa} = -\left(E + 2U_D\right); \\ r_{sa} = r + 2R_{ON} \\ \text{if } i_{sa} \le 0 \text{ have } u_{sa} = 0;\ r_{sa} = 2R_{OFF} \end{cases} \\ \text{if } ga(t) = -1 \text{ have } u_{sa} = -U; \\ r_{sa} = r + 2R_{ON}; \\ \text{if } ga(t) = 0 \text{ and } ga(t-h) = -1 \\ \text{have} \begin{cases} \text{if } i_{sa} < 0 \text{ have } u_{sa} = \left(E + 2U_D\right); \\ r_{sa} = r + 2R_{ON} \\ \text{if } i_{sa} \ge 0 \text{ have } u_{sa} = 0;\ r_{sa} = 2R_{OFF} \end{cases} \end{cases} \quad (20)$$

where $ga(t)$ is a pulse shaper ($ga(t) = 0$ – forms a positive pulse of current or voltage on the winding; $ga(t) = 0$ – there is no current on the winding;

$ga(t) = -1$ – the winding has a negative current or voltage pulse); h is the integration step in the implementation of the system of Equations (19), which describes the stepping motor; U is the supply voltage of the stepper motor; U_D – forward drop on the diode, $R_{ON} \ll R_{OFF}$ – public and private key resistance.

3. RESULTS

To implement the tracking system, we use a stepper motor, the parameters of which are given in Table 1.

Table 1. Stepper motor parameters

Parameter	Value
Nominal voltage, V	24
Rated current, A	3
Full-load torque, N·m	0,1
Rated frequency of steps execution, Hz	16000
Nominal moment of inertia of the load, kg·m^2	$4{\cdot}10^{-6}$
Unit step when using the driver,[degree	0,03
Nominal moment of inertia of rotor, , kg·m^2	$7{\cdot}10^{-6}$
Active resistance of the winding, Ohm	1±0,1
Winding inductance, mH	16±4
Limiting temperature rise of windings, °C	+170

Based on Figure 1 let's build a model in MatLab Simulink (Figure 4).

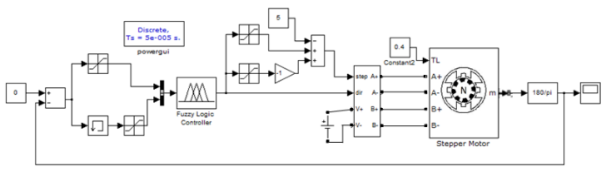

Figure 4 Model in MatLab Simulink.

Finding an error in the operation of the tracking system is calculated as the difference between the values obtained from the photoelectric sensor and the position of the panel at the current time relative to the Sun. If the panel position error does not correspond to the specified one, then a control signal is received from the logic controller to eliminate the error.

The transient response of the output signal versus time is shown in Figure 5.

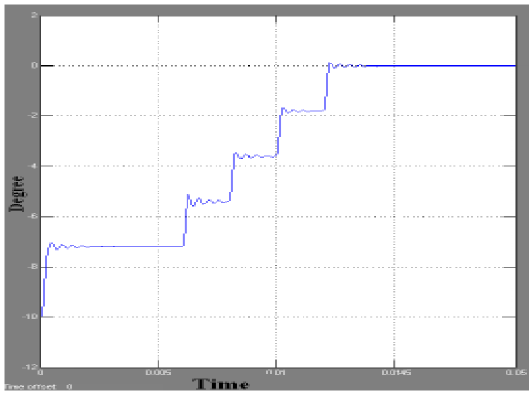

Figure 5 The transient response of the output signal.

Figure 6 shows the transient response of the electrical drive.

Table 2 shows the calculations of the energy consumption in the tracking mode of the stepper motor.

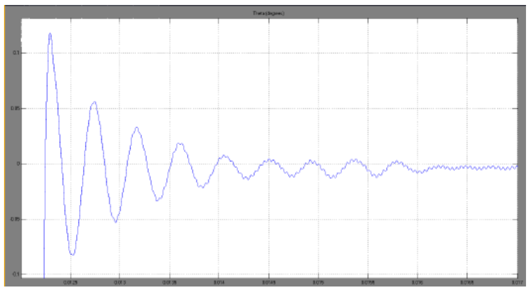

Figure 6 The transient response of the electrical drive.

Table 2. Power consumption of the stepper motor

Parameter	Value
Steady-state value of motor current , A	3
Motor voltage, V	24
Frame position change time by 3 degrees *t*, s	1,67
Frame position change time by 3 degrees, s	100,2
Steady state power, W	72
Required energy for two stepper motors at rest, kW·h	1,724

From the simulation results, it can be seen that the solar panel fulfils the required rotation angle, the motor overshoot is 1.2 %, and the transient time is 0.015 s.

4. SUMMARY

From the above results, it can be seen that the assumptions (20), in the control of tracking the consumption of energy expended for the shift from 4.0 to 4.8 %, the energy efficiency is increased when using the position distribution.

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