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ORIGINAL RESEARCH

Optimization of fuzzy entropy on solar panel's motor

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Abstract. Renewable energy has been in great demand by the public, even some countries have set regulations for substitution and transition from fossil energy to renewable energy. This study aims to modify the fuzzy control system with a metaheuristic method, namely fuzzy entropy. The entropy value of the fuzzy set in the previous stage becomes the basis for calculating the foot of uncertainty in the new fuzzy set. This process makes the entropy method parallel to other optimization methods that have been carried out on fuzzy control systems. The results obtained indicate that the modified fuzzy control system successfully controls the angular velocity of the solar panel. The error value shown is very small and the time to reach stability is below 5 second. This is a rapid development of several previous studies. The modified system has no overshoot and steady state error below 1%. Based on these results, entropy research can be developed again by changing the fuzzy set to a more complex form.

Keywords: Direct current motor, entropy, fuzzy logic controller, solar tracker, sun altitude.

INTRODUCTION

The Government of Indonesia has set a target of increasing the use of renewable energy in the national energy mix to 23% by 2025 [1]. This statement is found in government regulation number 79 of 2014, which relates to national energy policy [2]. In addition to the 2025 target, Indonesia is expected to be able to use 31% renewable energy by 2050 [3]. Renewable energy is also one of the government's 35,000 MW program's focal points. Renewable energy accounts for 25% of the program's total capacity, or 8,750 MW. Indeed, according to Presidential Regulation No. 22 of 2017 [4], Indonesia was still 95% dependent on fossil energy in 2015, while renewable energy accounted for only 5%. Solar energy is one type of renewable energy that is readily available in Indonesia. Indonesia's geographical location at the equator is one of the factors assisting in meeting the country's renewable energy targets. The average intensity of solar radiation in Indonesia is quite high, at around 4.8 kWh/m^2 per day [5].

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Solar panels, which are currently being mass-produced, are used in the solar energy harvesting process. The solar tracking system ensures that the solar panels receive sunlight. Researchers have conducted research on solar tracking systems using conventional PID control designs [6]. The results show that the model used does not accommodate the solar panel model, so efficiency cannot be calculated. Another study compared PID and T2FSMC and obtained data on the angular position of the motor based on constant angular velocity [7]. Mardlijah [8] shows how T2FSMC is used on a one-axis sun tracker to account for light intensity and the firefly algorithm during the optimization process. When compared to static solar panels, the results of the evaluation of the received solar radiation intensity are around 35% -38% in the design and implementation of two active solar tracking systems, one axis and two axes, and the maximum power efficiency increase is 20% [9].

The controller that uses fuzzy sets depends on setting the boundaries at the foot of the fuzzy set [10]. In certain cases, trial and error methods can solve control problems, but there are often uncertainties that require precise fuzzy adjustments [11]. This study proposes a method for developing fuzzy sets. Other studies have used several heuristic methods such as particle swarm optimization, firefly algorithm, and others [8,12]. The fuzzy entropy metaheuristic algorithm described in Oliva el al. [13] is used in the proposed method. Fuzzy entropy seeks the best value for each fuzzy set used to control solar panels. This article aims to form a fuzzy control system based on the entropy value of the fuzzy set. Within one degree of freedom, the control system follows the direction of motion. The assumption is that the sun's motion follows an angle ranging from 0° to 180°.

METHODOLOGY

Rotation motor model and fuzzy logic control

The development of technology that takes the position of the sun into account, or the so-called sun tracker, begins with a single axis model to track the direction of the sun's altitude or azimuth [14, 15]. This is followed by a two-axis sun tracker, which tracks the sun's position based on both its altitude and azimuth [16, 17].

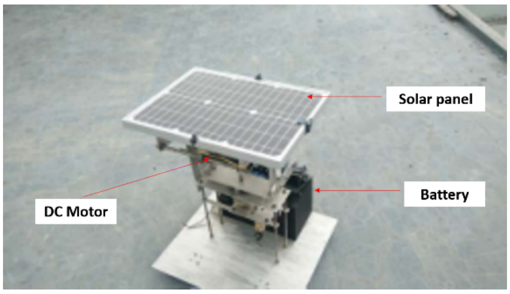

Figure 1. Prototype of solar panel [7]

Solar trackers are classified into two types based on their input data: passive trackers and active trackers. The active tracking system takes solar radiation sensitivity sensor data as input, whereas the passive method relies on manual settings based on solar trajectory calculations [18]. As a solar panel driver, this study employs a rotor model that faces the direction of the sun's rays. DC motor in Figure 1 is used as a drive with an east to west direction. This study only modeled the driving part, while the solar panel and battery parts were not included in the control system. As shown below, the model is simplified into a system of linear differential equations as follows [19].

$$\frac{di(t)}{dt} = \frac{1}{L}(E(t) - Ri(t) - K_b\omega(t)) \qquad (1)$$

$$\frac{d\omega(t)}{dt} = \frac{1}{J}(K_m i(t) - B\omega(t)) \qquad (2)$$

where the input voltage is expressed as *E(t)*. Equations (1) and (2) consider the current *i(t)* and angular velocity $\omega(t)$ as state variables. The system in Equations (1) and (2) uses the angular position $\theta(t)$ and parameters described in Table 1.

Table 1. DC motor parameters [7]

Parameter	Value
Electrical resistance R	18.2214 ohm
Electrical inductance L	0.000866 Henry
Electromotive torque K_b	0.030941093
Back electromotive torque K_m	0.030941093
Moment of inertia J	0.00009 Kg/m^2
Viscous friction B	0.000025 N.m.s

The system forms a linear differential equation with the outputs *i(t)* and $\omega(t)$. The controlling input is *E(t),* where the output $\omega(t)$ depends on the input value. the value of $\omega(t)$ becomes very large if the input given is also large, and vice versa. The value of *E(t)* is determined by the amount of error that occurred previously as a result of the value of *E(t)* given at the beginning of the simulation. The error is determined by the value of the angular velocity which is determined by the angular velocity of the sun's movement. Therefore, it needs two fuzzy sets type containing error as input and *E(t)* as output.

The fuzzy controller uses two fuzzy sets as controller inputs. The first set is the error *e* that occurs between the angle of the solar panel and the angle of the sun. The second set is the change in error Δe which is indicated by the differentiation of the error [20]. These two sets are divided into 5 linguistic variables, namely negative big (NB), negative small (NS), zero (Z), positive small (PS) and positive big (PB). The fuzzy controller considers its output as the input *E(t)* in Equation (1). The fuzzy sets formed are fast counterclockwise (CCWF), slow counterclockwise (CCWS), stop (S), slow clockwise (CWS), and fast clockwise (CWF).

Equations (1) and (2) are simulated with the help of the Simulink package in MATLAB. At this stage the fuzzy controller used is the fuzzy controller proposed in Ikhwan et al. [20]. Ikhwan et al. [20] resulted in a simulation with a large overshoot at the start of the simulation. It is a challenge for this article to eliminate the overshoot. Likewise with the steady state error, the resulting value is quite large. This article uses the entropy method to eliminate the overshoot and steady state error that occurs in Ikhwan et al. [20].

Fuzzy entropy

Fuzzy entropy is a fuzzy method development [21], and its application is more focused on reducing features in an image [22]. However, the fuzzy entropy method is now known to be an optimization method [13], specifically when applied to dynamic systems [23,24]. The use of fuzzy entropy can be seen in maximizing the entropy value for each possible fuzzy set, which is expressed as follows:

$$FOU = max(H) \tag{3}$$

$$H = -\sum_{i=0}^{n+1}\left(\sum_{j=0}^{L-1}\frac{p_j\mu_i(j)}{P_i}\cdot \ln\sum_{j=0}^{L-1}\frac{p_j\mu_i(j)}{P_i}\right) \tag{4}$$

$$p_i = h(i)/N, \qquad P_1 = \sum_{i=1}^{th_1} p_i\mu_1(i), \qquad P_2 = \sum_{i=th_1+1}^{th_2} p_i\mu_2(i), \ldots \quad P_{n+1} = \sum_{i=th_n+1}^{L-1} p_i\mu_n(i) \tag{5}$$

where the footprint of uncertainty (FOU) is the foot of uncertainty in the fuzzy set.

Fuzzy entropy is widely used in image processing where the L value is the length of the color histogram. In the control case, L is the number of possible solutions (histogram *h(i)*) that result where the range is a minimum to a maximum of $\omega(t)$. The value of N is the number of solutions produced, so that a certain solution value in the range L has a frequency in the range [0, N], meaning that the solution value $\omega(t)$ can be a maximum of N or be a constant value. While the value of n is showing the number of fuzzy sets used. This number is obtained from the number of fuzzy sets on the input and output. This article uses 2 fuzzy sets at the input and 1 fuzzy set at the output, so the number of fuzzy sets is n=3.

RESULTS AND DISCUSSION

Angle and angular velocity reference

The reference angle is calculated using two methods: sensors and models. Because the focus of this research is on the model as a basis for control, no sensor data is required. The angular velocity is obtained from the semicircle in radians divided by the daylight time, which is 12 hours. This assumption is based on natural events in which an object on Earth sees the sun from a different position each time. It takes the object 24 hours, or one day and one night, to see the sun at the same angular position. Because the earth's shape is spherical, with a cross section of a circle, the sun will be visible from objects on Earth for 12 hours, which is half the total time waiting for the sun to be visible at the same angle. As a result, it takes an angular distance of π degrees from the sun for objects on Earth to be visible.

$$0 \le \theta(t) \le \pi \tag{6}$$

$$\omega(t) = \frac{\pi}{12\ \text{hours}} = 7.3 \times 10^{-5}\ \text{rad/s} \tag{7}$$

Equation (6) shows the angle's range, while Equation (7) expresses the change in angle per unit time. This calculation is carried out based on the semicircle in radians divided by the daylight time assumption. In other cases, the angular position more accurately describes the reference or set of point (see [3][12][16][19][20]). This article follows the style of controlling the angular velocity reference $\omega(t)$ (see [1][7][8][11]).

Fuzzy sets and simulation results

The fuzzy set used is the fuzzy set in the previous study (see [20]). The FOU used is presented in Table 2 below:

Table 2. FOU of fuzzy sets [20]

FOU	**Input fuzzy sets**		**FOU**	**Output fuzzy set**
	e	**Δ*e***		***E(t)***
x_1	$-\frac{1}{2}\pi$	$-\pi$	y_1	-2
x_2	$-\frac{1}{4}\pi$	$-\frac{2}{3}\pi$	y_2	-1
x_3	0	0	y_3	0
x_4	$\frac{1}{4}\pi$	$\frac{2}{3}\pi$	y_4	1
x_5	$\frac{1}{2}\pi$	π	y_5	2

where x_i and y_i, for i = 1,2,3,4,5, are FOU. The value of x_i is the range obtained from the speed error or the change in the angular speed error of the driving motor that was formed before the control system was applied. The value of y_i is the voltage range given to the driving motor. Fuzzy membership function $\mu(x)$ and $\mu(y)$ are formed from FOU as follows:

$$\mu_{NB}(x) = \begin{cases} 0, & x < x_1 \\ 1 & x = x_1 \\ \frac{x-x_2}{x_1-x_2}, & x_1 \le x < x_2 \\ 0 & x \ge x_2 \end{cases} \tag{8}$$

$$\mu_{NS}(x) = \begin{cases} 0, & x < x_1 \\ \frac{x-x_1}{x_2-x_1} & x_1 \le x < x_2 \\ \frac{x-x_3}{x_2-x_3}, & x_2 \le x < x_3 \\ 0 & x \ge x_3 \end{cases} \tag{9}$$

$$\mu_Z(x) = \begin{cases} 0, & x < x_2 \\ \frac{x-x_2}{x_3-x_2} & x_2 \le x < x_3 \\ \frac{x-x_4}{x_3-x_4}, & x_3 \le x < x_4 \\ 0 & x \ge x_4 \end{cases} \quad (10)$$

$$\mu_{PS}(x) = \begin{cases} 0, & x < x_3 \\ \frac{x-x_3}{x_4-x_3} & x_3 \le x < x_4 \\ \frac{x-x_5}{x_4-x_5}, & x_4 \le x < x_5 \\ 0 & x \ge x_5 \end{cases} \quad (11)$$

$$\mu_{PB}(x) = \begin{cases} 0, & x < x_4 \\ \frac{x-x_4}{x_5-x_4} & x_4 \le x < x_5 \\ 1, & x = x_5 \\ 0 & x > x_5 \end{cases} \quad (12)$$

$$\mu_{CCWF}(y) = \begin{cases} 0, & y < y_1 \\ 1 & y = y_1 \\ \frac{y-y_2}{y_1-y_2}, & y_1 \le y < y_2 \\ 0 & y \ge y_2 \end{cases} \quad (13)$$

$$\mu_{CCWS}(y) = \begin{cases} 0, & y < y_1 \\ \frac{y-y_1}{y_2-y_1} & y_1 \le y < y_2 \\ \frac{y-y_3}{y_2-y_3}, & y_2 \le y < y_3 \\ 0 & y \ge y_3 \end{cases} \quad (14)$$

$$\mu_S(y) = \begin{cases} 0, & y < y_2 \\ \frac{y-y_2}{y_3-y_2} & y_2 \le y < y_3 \\ \frac{y-y_4}{y_3-y_4}, & y_3 \le y < y_4 \\ 0 & y \ge y_4 \end{cases} \quad (15)$$

$$\mu_{CWS}(y) = \begin{cases} 0, & y < y_3 \\ \frac{y-y_3}{y_4-y_3} & y_3 \le y < y_4 \\ \frac{y-y_5}{y_4-y_5}, & y_4 \le y < y_5 \\ 0 & y \ge y_5 \end{cases} \quad (16)$$

$$\mu_{CWF}(y) = \begin{cases} 0, & y < y_4 \\ \frac{y-y_4}{y_5-y_4} & y_4 \le y < y_5 \\ 1, & y = y_5 \\ 0 & y > y_5 \end{cases} \quad (17)$$

where $x \in \left[-\frac{1}{2}\pi, \frac{1}{2}\pi\right]$ and $y \in [-2,2]$ are error (rad) and voltage (Volt), respectively. The fuzzy rules used follow the rules carried out in previous studies [19,20].

After being simulated with a time of 15 seconds, it is found that the highest error value occurs at the beginning of the simulation (see Figure 2). This error is caused by the fuzzy controller that has a long time to reach stability because the rise time is around 0.4273 seconds. Before reaching a steady state position, the entropy system undergoes a large deceleration so that there is no overshoot derived from its predecessor. The time it takes to reach a steady position (settling time) is around 4.7893 seconds, after which time the error deviation is in a very small range.

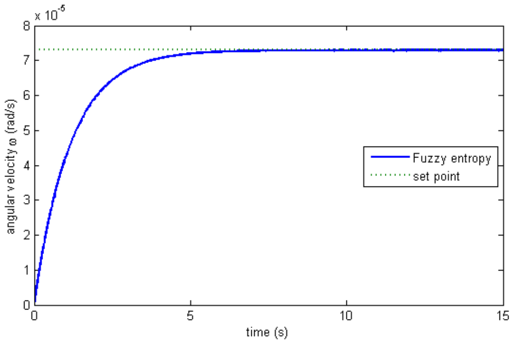

Figure 2. Simulation result at set point 7.3x10^{-5} rad/s.

The modified system succeeded in suppressing the overshoot almost close to the time of stability. In addition to a longer time to reach stability, the FLC system has a positional instability of almost 80% of the set point. It is what underlies the occurrence of errors at the beginning of control. Thus, the results obtained from the modified system show the novelty of the method with better accuracy.

This system at first glance is very close to the set point value. However, based on the simulation and the entropy value of each fuzzy set, there is a gap that occurs between the value of $\omega(t)$ and the set point. This is a weakness of the fuzzy entropy method, which eliminates every histogram that is at the end of the L range. The solution obtained eliminates the histogram *h(i)*=7.3x10^{-5} and the obtained frequency is shifted to the value *h(i)*=7.27x10^{-5}. The solution value is getting further away from the set point. As the iteration continues, the value of h(i) is getting further away from the set point and the error tolerance is not met. The method stops iterating and produces a solution as shown in Figure 2. Furthermore, Figure 3 explains the effect of excessive iterations caused by fuzzy entropy.

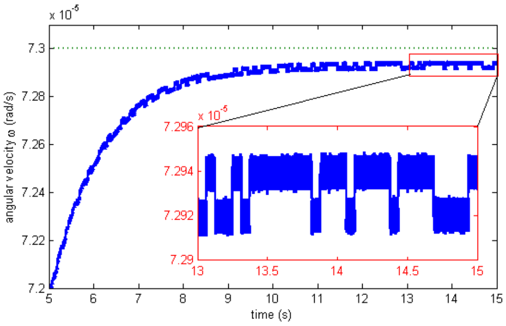

Figure 3. The steady state errors.

At the time of entering steady state, the system managed to be at the given tolerance. The fuzzy set produces an unstable value due to the uncertainty in the input and output sets. Over-interpretation leads to misinterpretation, for example, a value that drops slightly from steady state results in a slightly larger $E(t)$ and finally $\omega(t)$ also changes rapidly, and vice versa. It occurs from t=10 second until the end of the simulation.

Taking into consideration the amount of time and errors that occur in the steady position. This system turns out to have a small steady state error, reaching 0.005 to 0.009 or 0.07% to 0.1%. This performance is a very good finding for the optimization of entropy in solar panel motor control.

CONCLUSION

This study uses the theoretical definition of entropy as an optimization method. The entropy method has been used to extract features in real time data and image data. This extraction method is defined as a metaheuristic method. In the fuzzy set optimization method, entropy can determine the foot of uncertainty without the need for trial and error. This simplifies the process of controlling the solar panel motor system. The results obtained indicate an improvement in the performance of the fuzzy controller. This fuzzy control system is simpler because it only undergoes one modification, namely the determination of the foot of uncertainty, then the process runs according to how the fuzzy controller works. Because summarizing the process is simple, the process of determining results is shorter. Even so, the steady state error that occurs is quite large compared to several previous studies. This is because the fuzzy entropy discards some solutions near the set points and retains the solutions below them. In this case, fuzzy entropy performs excess iterations so that the solution histogram is eliminated in the process of forming a new fuzzy set. Judging from the steady state error, this system can be redeveloped by changing the fuzzy set to be more complex.

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