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ORIGINAL RESEARCH PAPER

Fuzzy entropy type II method for optimizing clean and renewable solar energy

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ABSTRACT

BACKGROUND AND OBJECTIVES: A solar panel is a device that converts solar rays into electricity. It is a step to reduce emissions from fossil energy, which is to replace it with renewable energy. It requires a control system to ensure that the position of the solar panel is always perpendicular to the sun's rays. This study aims to modify the fuzzy set based on fuzzy entropy in the control system that has been developed. The modifications made are expected to increase the efficiency of solar panels in harvesting energy.

METHODS: Type II fuzzy sliding mode control is used, along with a modified fuzzy set based on the entropy value. Before modification, the system containing the fuzzy set generates a histogram of entropy and voltage performance, which is the initial value and the comparison value. The algorithm alters the footprint of the uncertainty limit. This change results in a new fuzzy set, which results in a new histogram and voltage. The final step is to compare the initial and final parameters based on the results of the modifications.

FINDINGS: The solar panels require only 7.3x10-5 degrees of movement per second. This is a very slow movement for a dc motor with a maximum voltage of 12 volts. The simulation produced a stable speed of 7.297x10-5 on the unmodified system and 7.295x10-5 on the modified system. The modified system experiences a slight delay towards the stable point because the fuzzy entropy method reduces the dominance of set point positions in the system.

CONCLUSION: The modified fuzzy set is good at controlling the solar panel driving motor based on the output voltage value. On both controllers under consideration, the voltages follow the same pattern. However, it experienced a control mismatch at the point towards the set point. Finally, by changing the foot of uncertainty and adjusting it proportionally according to control needs, the control system based on fuzzy sets with fuzzy entropy can be further developed.

NUMBER OF REFERENCES	NUMBER OF FIGURES	NUMBER OF TABLES
35	7	2

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INTRODUCTION

Renewable energy-based power generation has the potential to reduce greenhouse gas emissions. Subsidizing the tariffs imposed on renewable energy can encourage energy generation, which leads to job creation through renewable energy generation. Renewable energy sources are very promising in Nigeria, Cameroon, Ghana, and South Africa, but government interest and policies are still low (Ibrahim *et al.,* 2021; Akinbami *et al.,* 2021). Governments in the former Soviet bloc play an active role in their renewable energy policies, including revising existing market-based instruments by imposing feed-in tariffs and offering tax incentives for renewable energy projects (Karatayev *et al.,* 2021). The use of renewable energy has become a separate issue in some countries, namely the rise in electricity costs. In Guatemala, more than a third of urban housing could see an increase in monthly energy expenditure (Henry *et al.,* 2021). The Indonesian government's goal is to increase the use of renewable energy in the National Energy Mix by 23% by 2025. This statement is found in Government Regulation No. 79 of 2014, which relates to National Energy Policy. Indonesia is expected to be able to use 31% renewable energy by 2050 (Rahman *et al.,* 2021). 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. In Indonesia, the average intensity of solar radiation is quite high, around 4.8 kWh/m^2 per day (Ikhwan *et al.,* 2019). The development of solar energy harvesting technology has resulted in a reduction in carbon dioxide emissions. The operation of the Mohammed bin Rashid Al Maktoum Solar Park in Dubai has saved 6.5 million tonnes of carbon dioxide equivalent, and this plant is expected to rise once all phases are completed and operational (Obaideen *et al.,* 2021). The control system on the solar panel drive system is being researched to ensure that the angle of the solar panel is facing the direction of the sun's rays. Many active and passive methods have been tried, but there is still a significant gap in the accuracy of the solar panel angle. The angle of incidence of sunlight on a sun tracker is known to be nearly equal to the active method (Sharma and Rohilla, 2021). This accuracy is affected by the light dependent resistor light sensor on the solar panel (Stefenon *et al.,* 2020). The passive drive system relies on the hypothesis that is built, so the set point approach is considered the most appropriate way to determine tracking accuracy. A fairly good approach at the set point can increase the amount of energy absorbed from solar radiation by 35.91% to 45.45% from systems that do not have controllers (Ayamolowo *et al.,* 2021). The application of a modified fuzzy system with a sliding surface yielded a very small error value (Ghiasi *et al.,* 2017). The addition of entropy value to fuzzy sets is a novel development in the production of control systems. The updated control system considers the difference in light intensity obtained as well as the timeliness of the setting. The system automatically returns the solar panel's position to face the sun. The energy absorbed by the solar panel can be maximized by keeping the angle facing the solar panel. This system can be used in other units that require precise sun positioning, such as navigation and location. 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. Another study was successful in comparing proportional, integral and derivative (PID) and Type II fuzzy sliding mode control (T2FSMC) and producing data on the angular position of the motor based on constant angular speed (Mardlijah *et al.,* 2017). T2FSMC has many advantages, including good control performance with a wide range of parameters and a faster response time (Hamzaoui and Al-Khazraji, 2011). T2FSMC was implemented on a one-axis sun tracker by Mardlijah *et al.* (2018), who used the firefly algorithm for optimization. The T2FSMC development method is proposed in this study, but it has the limitation of forming fuzzy sets (Mardlijah *et al.,* 2019). The T2FSMC method uses the fuzzy entropy type II (hereinafter referred to as fuzzy entropy) metaheuristic algorithm described by Oliva *et al.* (2019). Fuzzy entropy seeks the best value for each fuzzy set used to control solar panels. Fuzzy entropy is known as a physical concept of a vulnerability assessment model based on pattern recognition. Fuzzy entropy is clearer, and the evaluation results are reasonable and credible (Zhou *et al.,* 2022). At the Equator, a local control system was developed during the first year. 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° circle angles. Previously, research on the solar panel drive system was conducted using one axis and two axes of the sun's movement. However, there is still an angle error between the solar panel and the sun in these studies, which reduces the efficiency of solar energy absorption. This research proposes a new control system to improve the error performance between the sun's angle and the angle of the solar panel. Fuzzy Type-II Entropy Sliding Mode Control (T2FESMC) was developed. This method evolved from the FSMC and T2FSMC methods. In the previous control, the entropy value was used as an element of optimizing fuzzy sets in this study. This study is simulated at the Modeling and Simulation Laboratory, Department of Mathematics, Syiah Kuala University, Indonesia in 2021.

MATERIALS AND METHODS

The investigation begins with determining the reference angle, which is followed by the output of the control system. The control system began with SMC control and evolved into T2FSMC and T2FESMC. To determine the error value between the angle of the solar panel and the angle of the sun, simulations are run. System validation employs an integral time absolute error (ITAE) statistical measurement tool to detect and correct errors.

The reference angles

The reference angle is the angle of movement of the sun as seen from an object on the earth's surface. This angle is used as a reference to be followed by the developed control system. The reference angle is calculated using two methods: sensors and models. Because the focus of this study is on the model as a basis for control, no sensor data is required. Divide the semicircle by the amount of time the sun has moved to get the angular motion of one axis using Eqs. 1 and 2.

$$0 \le \theta \le \pi \tag{1}$$

$$\omega = \frac{\pi}{12\,\text{hours}} = 7.27 \times 10^{-5}\ \text{rad/s} \tag{2}$$

Where, θ in radians represents the sun's angle of movement and ω is the angular velocity of the reference being followed.

Fuzzy entropy

The application of fuzzy entropy type II can be seen in maximizing the entropy value for each possible fuzzy set which is formulated using Eq. 3 (Oliva et al., 2019), and Eqs. 4 and 5 (Zamri and Abdullah, 2013).

$$\max Tfe_k\left(\text{FOU}\right) = \sum_{k=1}^{nl+1} Fe_k \tag{3}$$

Where;

$$Fe_k = -\sum_{i=1}^{L-1}\left(\frac{h_i * \left(\mu_k^{high}(i) - \mu_k^{low}(i)\right)}{P_k}\right) * \ln\left(\frac{h_i * \left(\mu_k^{high}(i) - \mu_k^{low}(i)\right)}{P_k}\right), \tag{4}$$

$$k = \{1, \ldots, nl+1\}$$

$$P_k = \sum_{i=0}^{L-1}\left(h_i * \left(\mu_k^{high}(i) - \mu_k^{low}(i)\right)\right), k = \{1, \ldots, nl\} \tag{5}$$

By maximizing the total entropy, the value of each footprint of uncertainty becomes the solution using Eq. 2.

T2FESMC

The T2FESMC system is made up of three systems: sliding mode control (SMC), type II fuzzy (T2F), and type II fuzzy entropy (T2FE). SMC has long been recognized as an excellent controller for systems with uncertain values, such as solar panel models (Kchaou *et al.,* 2017). The SMC variable for fuzzy type II has the value using Eq. 6.

$$S_p = \frac{\dot{e} + \lambda e}{\sqrt{1+\lambda^2}} \text{ and } d = \sqrt{\left|e\right|^2 - S_p^2} \tag{6}$$

The use of SMC also has a good effect on research that uses the error value e and its derivative e as a variable that determines the amount of voltage to follow the sun's reference angle (Abadi *et al.,* 2015; 2020). The values of S_p and d are then entered into fuzzy type II. Both of these variables can be measured for each driving motor and the limits used can be

Table 1: The “and” relation between S_p and d parameters

d \ S_p	NB	NM	NS	NZ	PZ	PS	PM	NB
B	PB	PB	PB	PB	NB	NB	NB	NB
M	PB	PB	PB	PM	NM	NB	NB	NB
S	PB	PB	PM	PS	NS	NM	NB	NB
Z	PB	PM	PS	PZ	NZ	NS	NM	NB

updated for different types of DC motors. S_p and d are connected by the relation in Table 1.

Where, NB = negative big, NM = negative medium, NS = negative small, NZ = negative zero, PB = positive big, PM = positive medium, PS = positive small, PZ = positive zero. These rules are used to determine the range of membership functions S_p and d. The next step is to update the footprint value on the S_p and d variables by using entropy. Entropy is used for the optimization method described in Eq. 2. Accordingly, this method has been updated to T2FESMC which contains optimizations in it.

Simulation and validation

Simulation is carried out at one reference angle or the whole. However, in this study, the angular velocity becomes the reference because the angle followed changes with the same value every time. Any change in the angle of the sun's altitude must be followed by the pitch angle of the solar panels. The angular difference formed on the solar panel is referred to as the angular error, while the unstable angular velocity is referred to as the angular velocity error. The error value is the difference between the angle of the sun and the angle of the solar panel. Furthermore, validation is carried out using Eq. 7 (Rao *et al.,* 2020).

$$\mathrm{ITAE} = \int_{t=0}^{\infty} t\left|e(t)\right| dt \tag{7}$$

Where, ITAE is integral time absolute error, the value of *e(t)* is the difference y_i dan y, y_i is the angle of the sun and y is the external angle of the solar panel with the amount of n in the simulation time span *t*. If the ITAE value is very small, then the control system has succeeded in following the sun, but on the contrary, the MAE value is large enough, then the control system is repaired again with a larger entropy value. The value of y is obtained from the following motor system using Eqs. 8 and 9 (Ikhwan *et al.,* 2018).

$$\frac{di(t)}{dt} = \frac{1}{L}\left(E(t) - Ri(t) - K_b\omega(t)\right) \tag{8}$$

$$\frac{d\omega(t)}{dt} = \frac{1}{J}\left(K_m i(t) - B_f\omega(t)\right) \tag{9}$$

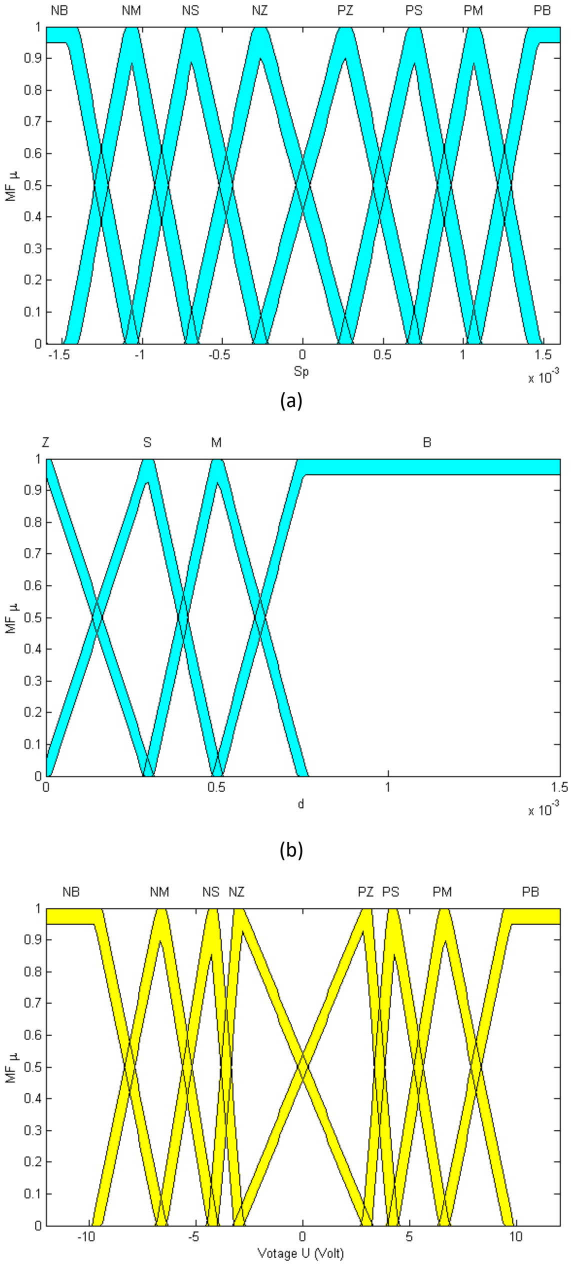
Where, the parameters used in Eqs. 8 and 9 are presented in Table 2.

RESULTS AND DISCUSSION

Recent development and analysis

The development is carried out using a combination of methods that are robust against existing disturbance conditions. A fuzzy logic controller and sliding mode control system has been introduced which is claimed to have robust properties compared to high calculation methods such as predictive control models. Mardlijah *et al.,* (2017) and Mardlijah *et al.* (2018) evaluated T2FSMC with two optimization methods, namely the firefly algorithm and the bisection approach. Both of them have small error values of 9.816×10^{-5} and 9.805×10^{-5}, respectively. Comparison of the two can be traced by remaking the system and simulated fairly. The system formed by the firefly algorithm is shown in Fig. 1.

Fig. 1 shows the fuzzy set used to control the solar panels. The vertical axis represents the membership function of the fuzzy set, while the horizontal axis represents the input parameter S_p in Fig.1(a), parameter *d* in Fig.1(b), and voltage output parameter *U* in Fig. 1(c). In Fig. 1(a) and (b), the outputs of SMC in the form of S_p and d are categorized as linguistic variables. The process continues by translating the previous two images into fuzzy output, namely in Fig. 1(c). The pre-set rules force two fuzzy sets for S_p and d to transform into voltage U. In this regulated system, only the variable voltage U is able to change the position of the solar panel so that it faces the



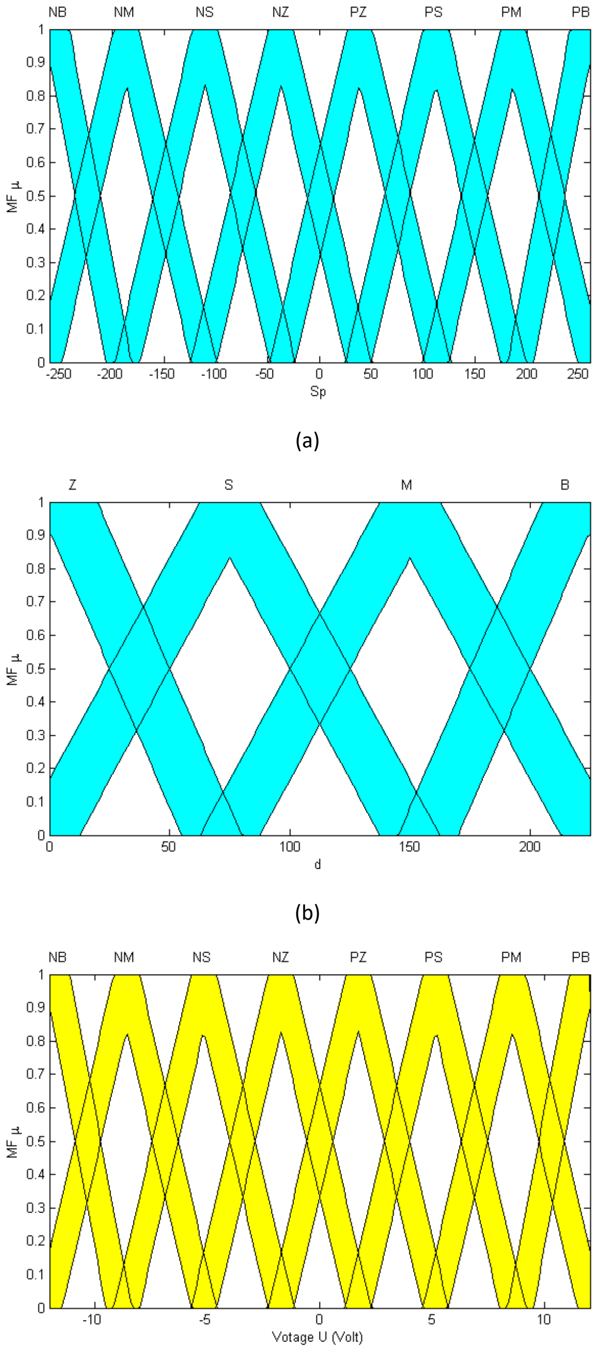
(a)

(b)

(c)

Fig. 1: T2FSMC with firefly algorithm

sun. The translation failure in Fig. 1(c) causes errors in the position and performance of the set of Fig. 1(a) and (b) must be modified again. The system formed in this control is not yet completely independent of the firefly algorithm. It is because of the effect of the gain magnifying parameter, which is set based on the smallest error value; it uses ITAE for this error value. The modified new control is the combination that produces the least ITAE. The novelty of this system is the reduction in the steady-state error value, but the computations required are lengthy because it is dependent on the distance of the parameter range. The resulting ITAE has a minimum value of 9.816x10^{-5} degrees and follows the sun's position perfectly. This development, however, cannot be regarded as the best combination. The performance of the fuzzy combination must still be analyzed and compared to the performance of other algorithm combinations.



(a)

(b)

(c)

Fig. 2: T2FSMC with bisection algorithm

Fig. 2 of the article reintroduces T2FSMC with a very fair and simple algorithm.

The workings of Fig. 1 are also adopted for Fig. 2. In fuzzy set planning, the assumption used is a proportional change in the entire system. Fig. 2 is made up of a fair distribution with the area of each fuzzy set not being differentiated. This even distribution is only seen as a set that can be enlarged and shrunk as needed. Mardlijah *et al.* (2017) measured and calculated both S_p and d values in real conditions, so that the two fuzzy sets in Fig. 2(a) and Fig. 2(b) are not subject to the bisection algorithm. The voltage output to the dc motor, however, is the main focus. The solar panels require only 7.3x10^{-5} degrees of movement per second. This is a very slow movement for a dc motor with a maximum voltage of 12 volts. It is important to note that if the voltage value remains high, the system will be inefficient and may even cause equipment damage. Starting from the range of values [0.1], the article proposes a reduction point using a bisection algorithm. The obtained value is 0.00012, allowing the sun's position to be tracked smoothly. Furthermore, the performance analysis of the two systems that have been formed is carried out on the error values Sp, d, and U. Figs. 3 and 4 are presented with a simulation that is fair and in accordance with the output of each algorithm.

Although the ITAE value is higher in the bisection algorithm, Fig. 3 on the left is more accurate. This is compared to the highest possible value for each error. Both S_p and d have a similar shape but differ in value to an accuracy of 1x10^{-7}. Although the method is the same, changes in the forming algorithm cause the accuracy value to change. Fig. 4 output is not significantly different from that of Fig. 3. The voltage produced by the firefly algorithm is more stable and lower in magnitude than the voltage produced by the bisection algorithm. Previous research (Mardlijah *et al.,* 2013) with a trial-and-error method resulting in a combination of fuzzy sets that direct the error value to be close to NZ and PZ is the main cause of this stable and small. That is, the other fuzzy sets have MF=0 and have no effect on the system's dynamics. This supports the results of the firefly algorithm, which show that the NZ and PZ areas are prioritized beginning with the second iteration, namely S_p and d errors.

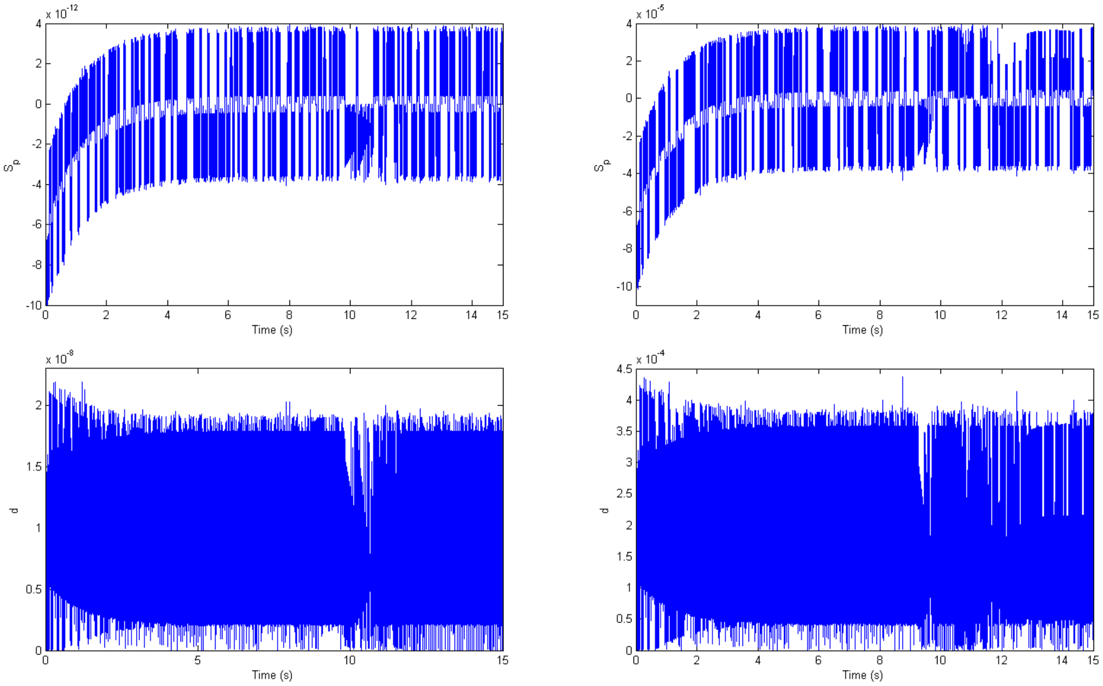
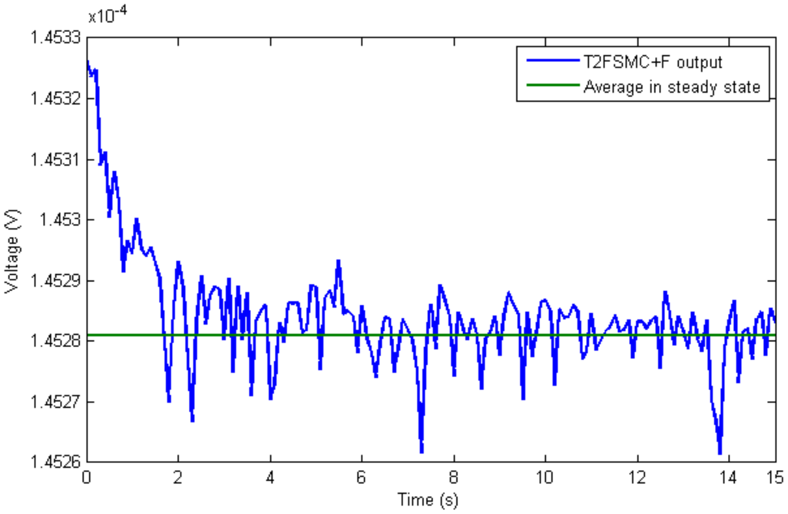
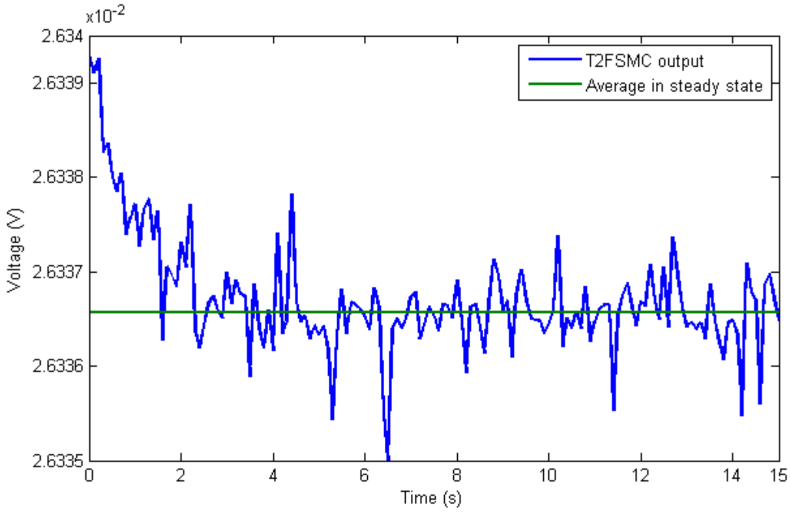


Fig. 3: S_p and d error values on T2FSMC (the firefly algorithm (left side) and the bisection algorithm (right side))



(a)



(b)

Fig. 4: Voltage output on T2FSMC (a) firefly algorithm, (b) bisection algorithm

Fuzzy entropy analysis

The analysis was performed on the previously discussed fuzzy set. This method has been modified because feature extraction adjustments are required. Fuzzy entropy can be used to calculate a new threshold for dividing the gray histogram on a grayscale image. The histogram division in the control problem, on the other hand, is in different ranges, namely [0 7.3×10^{-5}] with stepsize 1×10^{-7}. When the range is divided, a minimum of 729 new histogram data are obtained, which are included in Eq. (4) and Eq. (5). Prior to optimizing the entropy value, a fuzzy inference system was built to reference the histogram value h(i) and the membership function of each histogram. Starting with the previously discussed entropy value of T2FSMC, the results are very satisfying, with the total fuzzy entropy $T_{fe} = 5.4\times10^{-5}$. This value denotes those irregularities and uncertainties have values ranging from 5.4 to 12 Volts. Furthermore, the analysis is refined by gradually incorporating the footprint of uncertainty into the

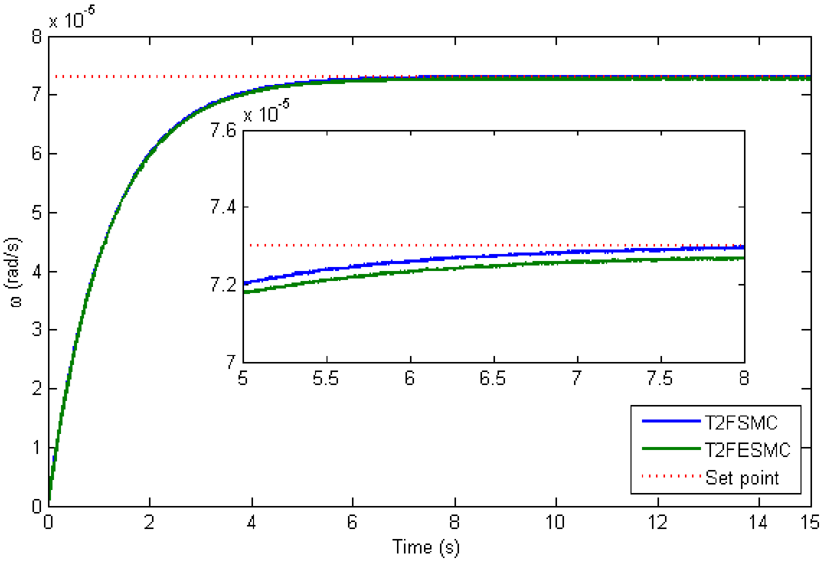


Fig. 5: Simulation of the new fuzzy inference system with the dc motor equation.

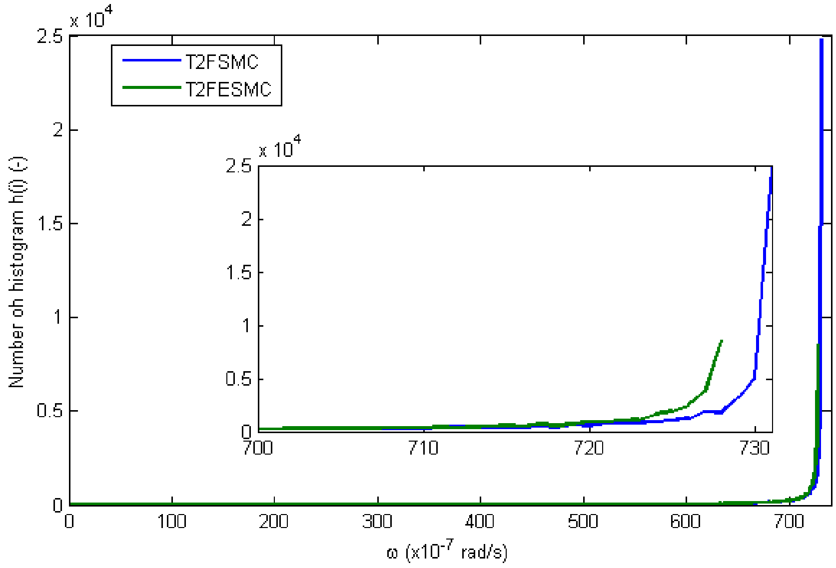


Fig. 6: The number of histograms h(i) in the conversion range [0.73x10^{-5}] with stepsize 1x10^{-7}

fuzzy set's legs. Fig. 5 depicts the simulation results of T2FSMC and T2FESMC after modification.

As a candidate control system, this system has succeeded in simulating and controlling the solar panel drive motor without using complicated calculations and only based on fuzzy set adjustments. The adjustment of the fuzzy set only takes two iterations due to the decrease in the total fuzzy entropy value which reaches 0.5x10^{-5}. The simulation is designed with a stop if there is a decrease in the total fuzzy entropy. The total fuzzy entropy obtained in the final iteration is 4.95x10^{-5}. This simulation generates a new histogram that can be analyzed. Fig. 6 explains that in the second iteration the total fuzzy

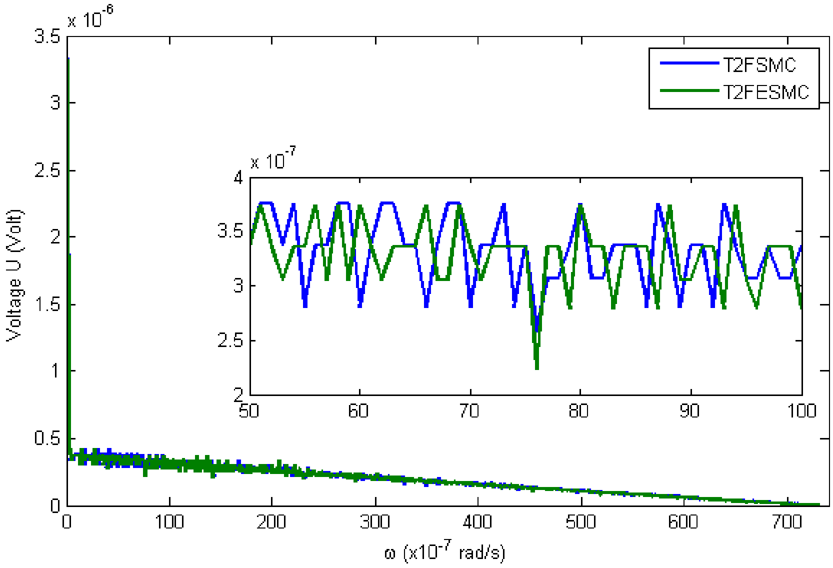


Fig. 7: Output voltage

Table 2: DC motor system parameters (Mardlijah *et al.*, 2018)

Parameter	Symbol	Value
Resistance	R	18.2214 Ω
Infuctance	L	0.000866 Henry
emf constant	K_b	0.030941093 V/(rad/s)
back-emf constant	K_m	0.030941093 N m/Ampere
Rotor inertia	J	0.00009 Kg m^2
Viscous friction coefficient	B_f	0.000025 N m s

entropy value decreases due to the decrease in the histogram close to the set point. This value is also influenced by the number of histograms before the peak. The T2FESMC is capable of matching histograms at low to moderate angular velocities. However, at high angular speeds, T2FESMC suffers from a lack of histograms. The number of histograms for T2FSMC is more than T2FESMC.

Reduction of the high value histogram on fuzzy entropy treatment is caused by incompatibility with the solar panel drive system. In the discussion of color histograms in black and white images, the application of fuzzy entropy is based on the dominant histogram division in the image (Mahajan *et al.,* 2021). The threshold that is formed eliminates the minor histogram by combining it with the nearby major histogram. While several major histograms that are close together, one of them is chosen to be the new threshold. This is different from the way solar panels work, which tries to be at set points. At the beginning of the simulation the position of the solar panels is far from the set point, so the system considered is a system that already has a major histogram at the set point as discussed in the bisection method at the beginning of this subsection. In this study, several major histograms that are already near the set point should produce a threshold that is at the set point. The fuzzy entropy algorithm does not accommodate this, so the set threshold is further from the set point.

The output voltage is the center of attention because the results in Fig. 7 are very similar. In addition to the decreasing fuzzy total value and the relatively low number of histograms, performance still has advantages in both systems. The fuzzy set used succeeded in producing the same voltage for both T2FSMC and the proposed system T2FESMC. The dynamics shown also have a range that is not much different and in the same trend. The resulting accuracy is also quite good reaching 1×10^{-7} and better than in Fig. 4. This voltage output can be used separately in all types of solar panels with the same parameters or close to the parameters in Table 2. In the end this comparison produces two different voltage outputs have the same trend so that the irregularities in the simulation can be handled properly. This system can also be digitized so that it can be easily applied to the prototype by taking a larger stepsize for the resulting voltage output.

CONCLUSION

The two previous control systems have been compared with their fuzzy entropy values. Both managed to control the solar panels according to the direction of the sun's rays. Although different optimization methods, both systems are known as former T2FSMC. Fuzzy entropy method is proposed to optimize the former T2FSMC, hereinafter referred to as T2FESMC. The results obtained are in accordance with the control requirements with a similar trend between the system that has been used and the proposed system. Based on the angular velocity as a set point, the modified fuzzy entropy lags slightly compared to T2FSMC. T2FSMC is faster towards the set point and then it oscillates slightly at steady state. T2FESMC is a bit late, but still keeps pace with T2FSMC. There is a slight change in the position of the solar panels compared to T2FSMC. In fuzzy entropy analysis, the total fuzzy entropy in T2FSMC is better than T2FESMC. It is due to the missing histogram division at values near the set point. Fuzzy entropy has an algorithm to determine a new threshold so that certain features can be eliminated. In this case, T2FESMC obtains a threshold value which causes the histogram to decrease near the set point value. In the iteration process, this algorithm does not eliminate histograms with large errors, but the histograms are removed proportionally from small errors to large errors. It means that the modification of fuzzy sets with fuzzy entropy does not guarantee that a more reliable control system will be obtained. The modified fuzzy set is very good at controlling the solar panel driving motor based on the generated voltage value. Voltages follow the same pattern in both controllers under consideration. The weakness of the modified system is that the shot is not strong at the beginning of the simulation, so the process to get to the set point is slower. However, when compared to the former T2FSMC, the applied voltage is similar and is still in a stable condition. Finally, the modification of the control system based on fuzzy sets with fuzzy entropy can be further developed by changing the foot of uncertainty and adjusting it proportionally according to control needs. A further challenge is the calculation of the energy obtained from the modified system and before the modification. Insignificant changes usually have little effect on the results that can be obtained. A faster computational process is also able to have a positive impact on controlling solar panels, so that the energy obtained can help substitute renewable energy. The modified control system applies not only to solar panels. The motor equation used in this study can generally be used for all types of systems that use a driving motor for solar tracking.

AUTHOR CONTRIBUTIONS

M. Ramli performed the literature review, running the model, analyzed and interpreted the data, prepared the manuscript text, and manuscript edition. M. Mardlijah performed the literature review, analyzed and interpreted the data, and manuscript edition. M. Ikhwan performed the literature review, prepared numerical code, prepared the manuscript text, and manuscript edition. K. Umam performed the literature review, analyzed and interpreted the data, and manuscript edition. All authors agreed on the final version of the manuscript.

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CONFLICT OF INTEREST

The authors declare no potential conflict of interest regarding the publication of this work. In addition, the ethical issues including plagiarism, informed consent, misconduct, data fabrication and, or falsification, double publication and, or submission, and redundancy have been completely witnessed by the authors.

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PUBLISHER'S NOTE

ABBREVIATIONS

%	Percent
°	Degrees (circle angles)
λ	Constant parameter
μ	Membership function
ω	rotor angular velocity (rad/sec)
ω_d	desired rotor angular velocity (rad/sec)
θ	Sun's angle of movement
B	Big
B_f	viscous friction coefficient (N-m/rad/sec)
d	distance between normal vector and sliding surface
E	Error
$\dot{e}$	First derivative of error
Eq /Eqs.	Equation
Fe_k	Fuzzy entropy on k index
Fig.	Figure
FSMC	Fuzzy sliding mode control
FOU	Footprint of uncertainty
H	Histogram
$i_a(t)$	armature current (Ampere)
ITAE	Integral time absolute error
J	rotor inertia (Kg-m^2)
$K_b(t)$	back-emf constant (Volt-sec/rad)
$K_m(t)$	torque constant (N-m/Ampere)
kWh/m^2	Kilowatt hours per square meter
L	Length of histogram
$L_a(t)$	armature inductance (Henry)
M	Medium
MW	Megawatt
No.	Number
NB	Negative big
NM	Negative medium
NS	Negative small
NZ	Negative zero
PB	Positive big
PM	Positive medium
PS	Positive small
PZ	Positive zero
$R_a(t)$	armature resistance (Ohm)
rad	Radians
rad/s	Radian per second
S	Small
S_p	distance between state vector and sliding
SMC	Sliding mode control
$T_m(t)$	load torque (N-m)
T2F	Type II fuzzy
T2FE	Type II fuzzy entropy
T2FESMC	Type II fuzzy entropy sliding mode control

T2FSMC	Type II fuzzy sliding mode control
Tfe_k	Total fuzzy entropy on k index
y	the external angle of the solar panel
y_i	The angle of the sun
Z	Zero

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