Hardware implementation of type-2 fuzzy logic control for single axis solar tracker

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ABSTRACT

Solar tracker widely maximizes solar energy harvesting by maintaining a perpendicular relative position between the sun and the solar panel. Single and dual-axis solar tracker controllers are the most control mechanisms that are widely implemented. The single-axis solar tracker (SAST) is preferable between those two control mechanisms due to economic and simpler control algorithm features. Many control algorithms have been proposed to improve the performance of SAST. The conventional proportional integral derivative (PID) controller has major limitations mainly corresponding to slower response. Moreover, it cannot handle the uncertainties of the sunlight. To overcome the problem, type 2-fuzzy logic control (T2-FLC) is proposed. The single-axis solar tracker controller based on T2-FLC is applied in Arduino and implemented in the hardware environment. It was monitored that the T2-FLC provides much better responses than the conventional controllers in terms of better dynamic response and more efficiency in harvesting solar energy.

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1. INTRODUCTION

Environmental issues and the continuous decrease of fossil fuel deposits have encouraged the massive development of renewable energy resources (RES) [1]. Among various RES, solar energy is the most popular RES widely implemented throughout the world [2]. It can be seen that the photovoltaic (PV) installed capacity and market has an enormous growth in recent year [3]. In 2020, the accumulation of global PV installation reached around 733.3 GW where Asia Pacific is the region that has the highest installed solar PV capacity around 341.9 GW [4]. Even though solar energy has been a prominent potential energy source for electricity needs, it is highly depended on the weather circumstances such as solar irradiance and surrounding temperature. The fluctuating nature characteristic of solar irradiation should be handled carefully to ensure stable power output of PV power plant. An efficient operation of PV generation under uncertain condition of solar irradiance and ambient temperature can be achieved by employing the control mechanism which is considered as maximum power point tracking (MPPT) methods.

Recently, a number of MPPT algorithms and designs have been proposed. MPPT methods can be classified based on several aspects such as sensing technique, tracking mechanism, and control algorithms in obtaining the maximum power from an actual solar irradiance condition [5]. In general, there are two approaches, i.e. mechanical (dynamic) and electrical (static) tracking, that can be implemented to extract the maximum power from the PV array [6], [7]. In the mechanical approach, the direction of PV panels dynamically changes with the movement of the sun in accordance with the change of the month and seasons, in the electrical approach, the PV panares is static and the MPP can be located using V-I curve.

Tracking systems are the popular methods to increase energy harvesting from actual solar irradiance circumstances. Even though the tracking mechanism has more complex and costly features, it has been proven can improve energy extraction in an efficient way. In general, single and dual-axis solar tracker controllers are the most control mechanisms that are widely implemented. The tracker mechanisms are classified according to the movements of solar panels either at the latitude or longitude axis. From energy conversion efficiency, the single and dual-axis solar tracker might increase energy harvesting by 12%-25% and 30%-45% respectively [8]–[10]. Among those two tracker schemes, the single-axis solar tracker is preferable due to economic and simpler control algorithm features. Moreover, the single-axis solar tracker is more suitable for small-scale PV generation.

Many control strategies have been developed to obtain the optimum operation of solar trackers. The conventional proportional integral derivative PID controller and fuzzy logic controller (FLC) have been widely implemented as solar tracking control schemes. Between those two controller algorithms, the PID controller has some drawbacks regarding the limitation of slow responses. It is also only suitable for controlling linear and negligible lag systems [11]. The FLC shows a better control performance in improving the system dynamic response. Compared to PID, the FLC presents a shorter settling time, smaller overshoot, and lower steady-state errors. Moreover, it steadied settling time according to the PID controller [12], [13]. Consequently, harvested energy from the sun increased significantly when T1-FLC was applied to the tracker. Conventional T1-FLC with five membership function (MF) was investigated in [12]. The MFs of input and output variables are determined using linear conversion from solar intensity to photo-sensor parameters. Different MF of T1-FLC was investigated in [14]. It was monitored higher number of MF provides better control performances as indicated by lower rise and settling time, lower overshoot, and hence increased harvesting energy from the sun. Most of the previous research uses FLC with common trapezoidal membership [11]–[14]. The typical FLC with that membership is popularly known as type-1 FLC (T1-FLC). Even though T1-FLC has some advantages over PID controller, the TI-FLC is less flexible when it was subjected to a complex system with a high level of uncertainty. To overcome this problem, the type-2 FLC (T2-FLC) is proposed [15]–[17]. The T2-FLC shows much better control performance than T2-FLC in terms of improving setting time and handling rule uncertainties [18]–[20]. The T2-FLC provides a more efficient control scheme and more accurate approximation specifically in a system with the uncertainties which appears due to measurement noise [20]–[22]. Moreover, the T2-FLC has more adaptiveness and shorter computational process since the T2-FLC may be used simultaneously in computing each bound of type-reduced interval [23]. In this paper, the T2-FLC is implemented as control algorithm for single axis solar tracker. The proposed control scheme should be able to handle uncertainties of solar irradiance due to sun movements and fast cloud covered circumstances. The T2-FLC would be compared to PID and T1-FLC to observe the effectiveness of the proposed control algorithm. Hardware implementation of T2-FLC based solar tracker is realized in Arduino platform. It is expected that the proposed control scheme would improve energy harvesting and hence increase the efficiency of single axis solar tracker.

The remainder of the paper is organized as follows. Section 2 presents the T2-FLC control algorithm. The development of single axis solar tracker (SAST) and hardware implementation are described in section 3. The simulation results and discussion of dynamic performance of the proposed controller are presented in section 4. Eventually, conclusions and contributions of the paper are highlighted in section 5.

2. METHOD

This section comprises two subsections, focusing on how the proposed method is designed. The first sub-section focuses on the theoretical approach of T2-FLC and the advantages of the proposed methods compared to conventional T1-FLC. The second sub-section represents a comprehensive design and development of a SAST based on T2-FLC. A hardware system of the investigated SAST is provided. Moreover, the design is MF of the proposed T2-FLC is explained.

2.1. Type-2 fuzzy logic control

The T2-FLC is the development of type-1 fuzzy sets that allow a higher level of uncertainties which might be appears due to the uncertainties about; i) the meaning of the words in the rules, ii) consequent in the rules, iii) measurement that activates the FLC, and iv) data that are used to tune the FLC parameters. In T1-FLC, a precise MF is used to present uncertainties correlated to the meaning of the words. Consequently, once the MF is determined, the nature of uncertainty about the words would disappears.

The T2-FLC can be considered as an improvement of T1-FLC in handling the uncertainty not only limited to the linguistic variables but also the MF [20], [24]. The concerns of uncertainties correlated to the meaning of the word in the rules in FLC are better defined and accommodated in the T2-FLC by providing more flexible boundaries of the fuzzy sets. The consequents of the rules are presented in a histogram of possibilities. it also considers strife or conflict among the various sets of alternatives solutions, providing more realistic rules of the real-world problems. The uncertainties measurement that activates the FLS are presented with non-specificity when associated with the information-based data imprecision. It prevents misleading assumptions of the probability model for either the signal of the noise. From the data point of view, the T2-FLC can better handle the uncertainty of data that are used to tune the parameters of FLC. With all the superiority, it can be considered that the T2-FLC can directly address all three types of uncertainties: fuzziness, strife and non-specificity [25].

Figure 1 shows the structure of T2-FLC. In general, the structure of T2-FLC is similar to T1-FLC except in output processing stage which consisting of defuzzification type-reducer procedures. In fuzzifier stage, the input crips are mapped into a fuzzy set. The inference scheme combines rules and maps the correlation between input T2-FLC sets and output T2-FLC sets. The T2-FLC output crips are calculated using similar defuzzification procedure in T1-FLC with the extension on the "type-reduced set operation". Hence, to completely build a T2-FLC, some procedures should be addressed involves performing theoretical set operation, identifying the membership grades of T2-FLC sets, dealing with T2-FLC relation and compositions and performing type reduction and defuzzification process to determine values of output crips [19], [20].

The MF of T2-FLC should be carefully selected hence it can handle uncertainties. Among various MF, the triangles MF is the most popular MF for the T2-FLC as depicted in Figure 2. In general, the MF of T2-FLC is a three dimensions MF considering footprint of uncertainty (FOU). The FOU provides the information correlated to the degree of data sets uncertainties. It can be described with the boundary functions of lower membership function (LMF) and upper membership function (UMF).

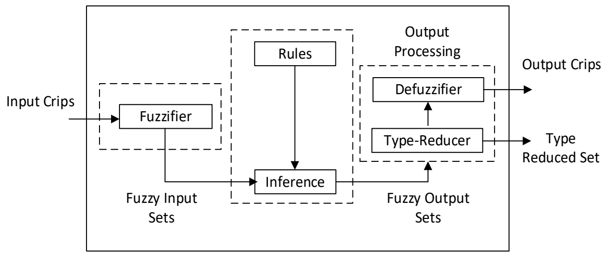


Figure 1. T2-FLC system [20]

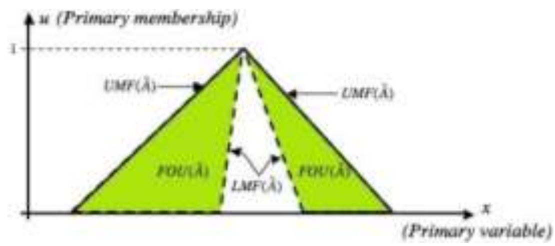


Figure 2. Type-2 fuzzy set

The input crips are processed into a fuzzy set through fuzzifier process on LMF and UMF, obtaining two fuzzy values in a primary MF. The stages of type-2 fuzzy logic are fuzzification, fuzzy inference system, type reduction, and defuzzification. The fuzzification process is carried out on the LMF and UMF degrees, resulting in two fuzzy set values with the same membership. In the fuzzy inference system, the operation is used to combine information from two fuzzy sets into one fuzzy set. This operation has the aim of illustrating the extent of the relevance of the two fuzzy sets. This operation can be performed using the min-max intersection method.

Type reduction is a process used in type-2 fuzzy logic to convert type-2 fuzzy sets into type-1 fuzzy sets. This process is useful for reducing the complexity of the type-2 fuzzy set. This process can be done using the centroid method. This method calculates the centre of the type-2 fuzzy set as a representation of the type-1 fuzzy set. The centroid calculation is shown in (1).

$$C_A = \frac{\int_{-\infty}^{\infty} x[UMF_A(x) - LMF_A(x)]dx}{\int_{-\infty}^{\infty}[UMF_A(x) - LMF_A(x)]dx} \quad (1)$$

Where C_A is the center of the type-2 fuzzy set A on variable x. Integration is performed over the entire relevant x domain. This center is a single value that represents the distribution center of the type-2 fuzzy set A in the form of a type-1 fuzzy set. In this way, the complexity of the type-2 fuzzy set is reduced to a type-1 fuzzy set with a lower degree of uncertainty, which is easier to use in decision-making or analysis.

The interval approach method provides numerical intervals involving the degree of uncertainties as the results of T2-FLC operation. It enables simpler implementation in analyzing and determine the decision. The calculation of interval approach is given by (2).

$$[\underline{A}(x), \overline{A}(x)] = [inf_x UMF_A(x), sup_x LMF_A(x)] \quad (2)$$

Where $[\underline{A}(x), \overline{A}(x)]$ is the numerical interval that involves the cirps of T2-FLC A on a certain variable x. The $inf_x UMF_A(x)$ and $sup_x LMF_A(x)$ represent the infimum and supremum values from upper and under MF respectively.

The Karnik-Mendel method is one of the more complex approaches in reduction type process. This method considers the probabilistic distribution in T2-FLC crips which result in more accurate reduction process. The Karnik-Mendel method uses. Centroid calculation to calculate the centre and width calculation from T2-FLC crips. The calculation of T2-FLC is given as (3).

$$W_A = \int_{-\infty}^{\infty} UMF_A(x)dx - \int_{-\infty}^{\infty} LMF_A(x)dx \quad (3)$$

Where $\int_{-\infty}^{\infty} UMF_A(x)dx$ is the area from upper MF curve while $\int_{-\infty}^{\infty} LMF_A(x)dx$ represents the area of lower MF curve. The crips width provides important information regarding the variation or uncertainties in the results of T2-FLC crips which can be used in analysis or decision making.

2.2. SAST system

In this paper, a small scale SAST is developed as shown in Figure 3. The SAST mechanism is an approach method to increase the harvesting of solar energy. It allows solar panel to follow the sun movements in along one axis either latitude or longitude depending on the position of solar power plant. The SAST is widely implemented specifically for small scale PV generation due to more economic and simple structure compared to dual axis solar tracker (DAST) system. It has one degree of freedom since it can track the sun in one axis only.

Figure 3. Single axis solar tracker (SAST) system

The investigated SAST is equipped with 100 Wp polycrystalline solar panel and two light depended resistor (LDR) GY 49 sensors. The LDR sensors are installed at the top of the solar panel and each sensor are separated with a small acrylic separator. The DC motor of 12V, 12 mm/s 100 kg linear/tubular is considered as a movement mechanism. Moreover, the current (ACS712) and voltage sensors were also applied in order to monitor the performance of single axis solar tracker. The control system of DAST was implemented along with Arduino development board. The Arduino system has an Atmel AVR processor and uses its software and language. Arduino Nano is a microcontroller development board based on the ATmega328 (for Arduino Nano version 3.x) or ATmega 168 (for Arduino version 2.x) microcontrollers. The SAST system is equipped with two LDR sensors to read the sunlight intensity values. MPP is obtained when relative position of sun and solar tracker is perpendicular. Under the change of sun's position and solar irradiation calues, the linear actuator would move either in clockwise or counterclockwise roation to obtain optimum position between solar panel and sun. The roation of lienar actuator would stop when the difference values between those two LDR sensors is equal to the tolerance value. It means that the MPP is achieved. The tolerance value is determined according to the sensitivity of the sensors [12].

Block diagram of the SAST hardware system is depicted in Figure 4. The values of LDRs are used as input of the proposed T2-FLC that will be processed by the Arduino Nano microcontroller module as a fuzzy logic controller. Linear actuator is used to adjust the facing position of the solar panel. The motor driver is needed as a current amplifier so that the microcontroller module can adjust the rotation of the linear actuator.

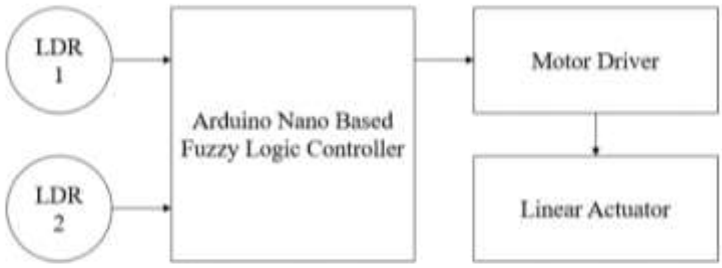
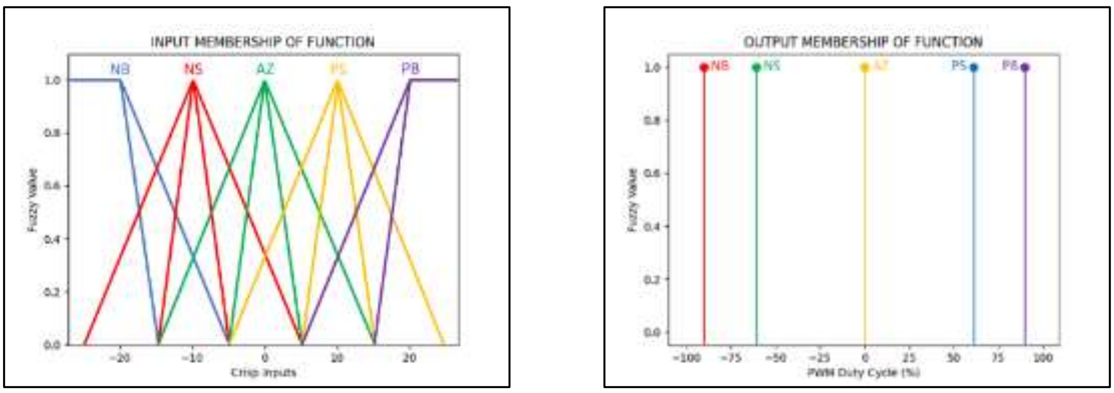


Figure 4. Hardware system

The software is built using the C++ programming language that would be embedded in the Arduino Nano microcontroller module. The crisp inputs consist of two values; the difference between the LDRs sensor readings at t and t-1. The fuzzification process is carried out to convert the value of the crisp inputs into a fuzzy value. Fuzzification is conducted using the input MF in the T2-FLC method. The results of the fuzzification process are then used as a reference value for the inference process to decide on the applicable rules. The diagram of MF of T2-FLC is depicted in Figure 5. It can be further described as input and output MF of the T2-FLC as presented in Figure 5(a) and (b) respectively.



(a) (b)

Figure 5. Membership function of (a) input and (b) output of the system

The defuzzification process is implemented according to the fuzzy rules that have been applied in the previous process and the membership of function output to produce a crisp output value. The obtained output values determine the duty cycle of a pulse width modulation (PWM) to adjust the speed of the linear actuator hence it can change the facing position of the solar panel. The attributes of the fuzzy rules consist of negative big (NB) at a duty cycle of -90%, negative small (NS) at a duty cycle of -60%, almost zero (AZ) at a duty cycle of 0%, positive small (PS) at a duty cycle of 60%, and positive big (PB) at a duty cycle of 90%. The negative number represents the orientation setting of the linear actuator which follow the counterclockwise rotation, and the positive number represents the orientation setting of the linear actuator which follow the clockwise rotation. The set of proposed fuzzy rules used in this research is represented in Table 1.

Table 1. T2-FLC rule base

Input 1	Input 2	Output
Negative big	Negative big	Negative big
Negative big	Negative small	Negative big
Negative big	Almost zero	Negative big
Negative big	Positive small	Negative big
Negative big	Positive big	Negative big
Negative small	Negative big	Negative big
Negative small	Negative small	Negative small
Negative small	Almost zero	Negative small
Negative small	Positive small	Negative small
Negative small	Positive big	Negative small
Almost zero	Negative big	Negative small
Almost zero	Negative small	Almost zero
Almost zero	Almost zero	Almost zero
Almost zero	Positive small	Almost zero
Almost zero	Positive big	Positive small
Positive small	Negative big	Positive small
Positive small	Negative small	Positive small
Positive small	Almost zero	Positive small
Positive small	Positive small	Positive small

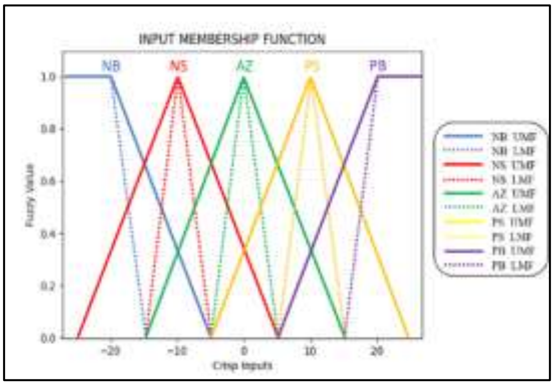
3. RESULTS AND DISCUSSION

The critical concern in developing SAST is how to deal with the complexity of mechanical systems and the uncertainty of solar irradiance. Many control algorithms have been proposed to improve the dynamic performance of SAST to efficiently track the sun's movement. Some drawbacks of the proposed control methods have been reported. The conventional PID controller offers a simpler control algorithm. However, it has some limitations in terms of slower response and is only suitable for a linear system with less degree of uncertainty. For an uncertain circumstance such as fluctuating conditions of solar irradiance and a non-linear complex system such as SAST, the fuzzy logic controller can be implemented to address the limitation of PID controller. Even though the T1-FLC has a better dynamic performance over PID controller, it has less flexible MF when implemented to a complex system. To overcome the problem, this research proposes T2-FLC based control method for improving the performance of SAST. It is suggested that the T2-FLC provides a better response and dynamic performance over PID and T1-FLC such as faster setting time, lower overshoot and smaller steady state error.

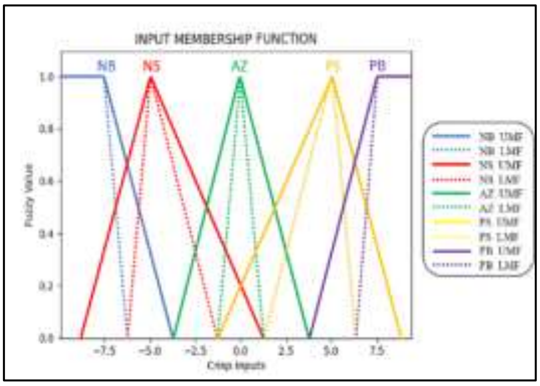
The investigated SAST is equipped with 100 Wp polycrystalline solar panel and two LDR GY 49 sensors. The DC motor of 12V, 12 mm/s 100 kg linear/ tubular is considered as movement mechanism. A good selection of MF in T2-FLC is critical to obtain a good performance of SAST in tracking the sun position and handling uncertainties of solar irradiance. Variation of several MF configuration is necessary to obtain an optimal MF for SAST. In this paper, three sets of input MF are considered to find the best MF of T2-FLC. Selection of T2-FLC MF is conducted by comparing the dynamic response of SAST when it is subjected to the change of sun position. In this paper, it is considered that the best MF of T2-FLC is selected based on the best response of the SAST when the initial position of the solar panel is set at 40° and the position of the light which mimicking the sun is at an angle of 90°. The investigated MF for T2-FLC is depicted in Figure 6. Figure 6(a) presented the MF of model 1. While Figures 6 (b) dan (c) show the MF model 2 and 3.

The comparison of SAST dynamic response and settling time of three MF are shown in Figure 7 and Table 2 respectively. When the SAST is required to follow the sun position, it is monitored that the model 2 MF provides a better response compared to model 1 MF and model 3 MF. The least oscillatory and fastest settling time is observed in model 2 MF. Therefore, the model 2 MF is selected as input crips for proposed T2-FLC based SAST.

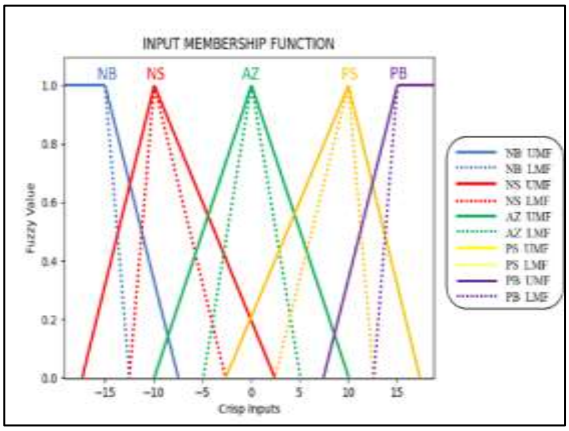
The dynamic performance of the SAST with selected MF of T2-FLC is then compared to the conventional SAST-based T1-FLC. The comparison of system dynamic responses and settling time of T1-FLC and T2-FLC are depicted in Figure 8 and stated in Table 3 respectively. Higher settling time is observed when the T1-FLC is applied, resulting in a slower response of the SAST under the change of sun's position. Consequently, the SAST cannot follow the sun's movement effectively, especially during cloudy and windy circumstances. Improvement of the dynamic performance of the SAST is observed when T2-FLC is implemented as indicated by shorter settling time, less oscillatory condition, and lower overshot. Therefore, it might result in higher measured solar irradiance on the solar panel surface. Eventually, higher energy harvesting and more efficient SAST are obtained.



(a)



(b)



(c)

Figure 6. Three models of input membership functions: (a) model 1, (b) model 2, and (c) model 3

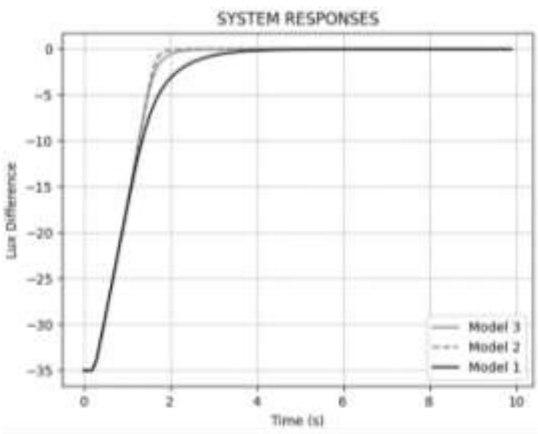


Figure 7. Comparison of three T2-FLC MF

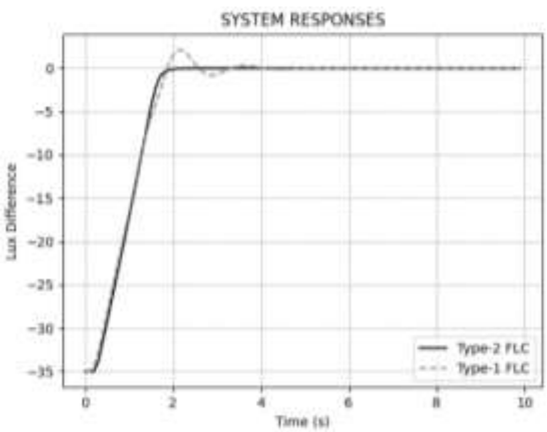


Figure 8. T1-FLC and T2-FLC dynamic performances

Table 2. Settling time comparison of T2-FLC set model

T2_FLC set model	Settling time (s)
1	3.9
2	1.9
3	2.2

Table 3. Settling time comparison for T1-FLC and T2-FLC-based SAST

Fuzzy model	Settling time (s)
Type-1	4.7
Type-2	1.9

The performance of proposed T2-FLC controller is further tested under real-time scenarios of fluctuating solar irradiance circumstances. Two identical SASTs with T1-FLC and T2-FLC algorithms are considered. The tracking performances of those two SASTs are real-time monitored from 06:00 am to 02:30 pm with 1 minute data sampling. Measured irradiation values, terminal voltage and output power from the SASTs are observed to investigate the effectiveness of the proposed control algorithm. The real-time monitoring of solar irradiance is depicted in Figure 9. A windy with scattered clouds is experienced during the experiment. Consequently, the irradiation values on solar panel are fluctuated significantly. Under fluctuating condition of received solar irradiance on the solar panel surface, the proposed T2-FLC significantly improves the tracking performance of the SAST compared to the T1-FLC algorithm. Faster dynamic response of the T2-FLC based SAST results in more efficient and precise solar panel movement in maintaining the perpendicular relative position between sun and solar panel. The improvement of tracking ability of the SAST with T2-FLC is reflected in a higher measured solar irradiation on the panel surface. Moreover, it is also suggested that the proposed control algorithm can handle uncertain condition of solar irradiance under unpredictable weather circumstances.

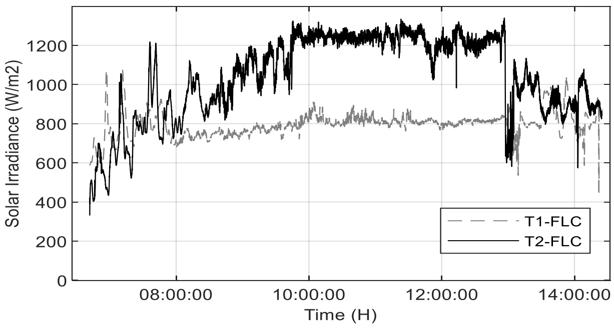


Figure 9. Comparison of measured solar irradiance on solar panel

Voltage and power information measured from the SAST with two types of FLC are further observed. From Figure 9, it is monitored that potential energy harvesting from solar irradiance is higher when the T2-FLC is applied. It is expected that the more potential energy harvested, the more electrical energy can be generated. One important concern in implementing RES involving PV generation is the difficulties to ensure voltage stability under solar irradiance variations. Under a sunny weather, the relative movements of SAST are minimum. Hence, the stability of voltage output can be maintained. However, during uncertain weather conditions such as scattered and fast cloud circumstances, it is difficult to maintain a stable voltage due to frequent and inaccurate movements of SAST. To maintain a stable voltage output of solar panel under fluctuating condition of weather and solar irradiance, it is necessary to have a precices control system with a sufficient sensitivity degree. Real time experiment is conducted to investigate the performance of proposed control algorithm. It is clearly monitored that the proposed T2-FLC provides more stable output voltage compared to T1-FLC based SAST. Less fluctuated terminal voltage of solar panel is observed when the T2-FLC is implemented on SAST. Moreover, due to more precise positioning of solar panel with T2-FLC in maintain optimum position relative to the sun, higher terminal voltage is also observed, resulting more reliable and stable output voltage. The comparison of terminal voltage of SAST with T1-FLC and T2-FLC is depicted in Figure 10.

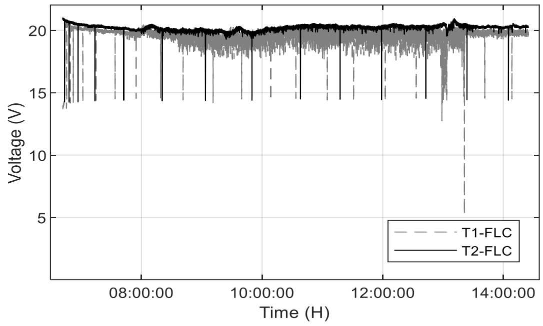


Figure 10. Comparison of measured terminal voltage

Figure 11 represents the comparison of output power of SAST with the two investigated control algorithms. The generated output power of PV generation increases proportionally with the increase of obtained solar irradiation. As T2-FLC based SAST provides a superior performance in harvesting potential energy from solar irradiation, the output power generated from the SAST based T2-FLC increased significantly compared to SAST based T1-FLC, resulting improvement of system efficiency.

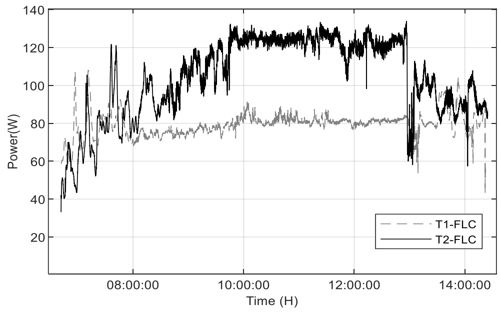


Figure 11. Comparison of output power

The presented results suggested that the T2-FLC based control algorithm of SAST is more resilient than T1-FLC control methods, especially in handling uncertainty of solar irradiance under fluctuated and unpredicted weather conditions. Future research in optimizing the MF of T2-FLC can be conducted to further improve the dynamic performance of SAST. Moreover, it also can be considered to combine a metaheuristic control method with T2-FLC to handle uncertainties in SAST due to fluctuating condition of solar irradiance and weather.

4. CONCLUSION

This paper presents the development of a T2-FLC based SAST. The proposed control algorithm is applied in Arduino and implemented in the hardware environment. The performance of the controller is compared to conventional T1-FLC. It was monitored that the T2-FLC provides much better responses and dynamic performance than the conventional controllers in terms of faster settling time, less oscillatory conditions, and lower steady-state errors. Furthermore, it denotes that the proposed controller is more efficient and precise in obtaining and maintaining the optimum position of the solar panel, resulting in higher potential energy harvesting from solar irradiance. Consequently, the generated output power in SAST-based T2-FLC is higher than in SAST-based T1-FLC. Moreover, the proposed control scheme improves the voltage stability performance of SAST as indicated by more stable terminal voltage under fluctuating condition of solar irradiation.

REFERENCES

[1] H. Setiadi *et al.*, “Multi-mode damping control approach for the optimal resilience of renewable-rich power systems,” *Energies*, vol. 15, no. 9, 2022, doi: 10.3390/en15092972.

[2] Y. Chi, Y. Xu, and R. Zhang, “Many-objective robust optimization for dynamic VAR planning to enhance voltage stability of a wind-energy power system,” *IEEE Transactions on Power Delivery*, vol. 36, no. 1, pp. 30–42, 2021, doi: 10.1109/TPWRD.2020.2982471.

[3] H. M. Sultan, A. A. Z. Diab, O. N. Kuznetsov, Z. M. Ali, and O. Abdalla, "Evaluation of the impact of high penetration levels of PV power plants on the capacity, frequency and voltage stability of Egypt's unified grid," *Energies*, vol. 12, no. 3, p. 552, 2019, doi: 10.3390/en12030552.
[4] B. Looney, "Statistical review of world energy 2021," *BP Energy Outlook 2021*, vol. 70, pp. 1–70, 2021.
[5] A. O. Baba, G. Liu, and X. Chen, "Classification and evaluation review of maximum power point tracking methods," *Sustainable Futures*, vol. 2, p. 100020, 2020, doi: 10.1016/j.sftr.2020.100020.
[6] A. K. Podder, N. K. Roy, and H. R. Pota, "MPPT methods for solar PV systems: a critical review based on tracking nature," *IET Renewable Power Generation*, vol. 13, no. 10, pp. 1615–1632, Jul. 2019, doi: 10.1049/iet-rpg.2018.5946.
[7] P. Bhatnagar and R. K. Nema, "Maximum power point tracking control techniques: state-of-the-art in photovoltaic applications," *Renewable and Sustainable Energy Reviews*, vol. 23, pp. 224–241, Jul. 2013, doi: 10.1016/j.rser.2013.02.011.
[8] R. Singh, S. Kumar, A. Gehlot, and R. Pachauri, "An imperative role of sun trackers in photovoltaic technology: a review," *Renewable and Sustainable Energy Reviews*, vol. 82, pp. 3263–3278, Feb. 2018, doi: 10.1016/j.rser.2017.10.018.
[9] S. Motahhir, A. El Hammoumi, A. El Ghzizal, and A. Derouich, "Open hardware/software test bench for solar tracker with virtual instrumentation," *Sustainable Energy Technologies and Assessments*, vol. 31, pp. 9–16, Feb. 2019, doi: 10.1016/j.seta.2018.11.003.
[10] L. A. S. Ferreira, H. J. Loschi, A. A. D. Rodriguez, Y. Iano, and D. A. Do Nascimento, "A solar tracking system based on local solar time integrated to photovoltaic systems," *Journal of Solar Energy Engineering, Transactions of the ASME*, vol. 140, no. 2, Apr. 2018, doi: 10.1115/1.4039094.
[11] A. K. Singh, Y. Chauhan, and N. Sharma, "Comparative performance analysis of intelligent controllers for solar tracking system," *Materials Today: Proceedings*, vol. 65, pp. 3731–3740, 2022, doi: 10.1016/j.matpr.2022.06.388.
[12] E. Kiyak and G. Gol, "A comparison of fuzzy logic and PID controller for a single-axis solar tracking system," *Renewables: Wind, Water, and Solar*, vol. 3, no. 1, p. 7, Dec. 2016, doi: 10.1186/s40807-016-0023-7.
[13] J. J. Ontiveros, C. D. Avalos, F. Loza, N. D. Galan, and G. J. Rubio, "Evaluation and design of power controller of two-axis solar tracking by PID and FL for a photovoltaic module," *International Journal of Photoenergy*, vol. 2020, pp. 1–13, Jul. 2020, doi: 10.1155/2020/8813732.
[14] I. Abadi, C. Imran, and N. Fasa, "Smart solar tracking system based on fuzzy-PI controller for maximizing the power of PV," in *AIP Conference Proceedings*, vol. 2088, p. 020022, 2019, doi: 10.1063/1.5095274.
[15] Y. Away, A. Rahman, T. R. Auliandra, and M. Firdaus, "Performance comparison between PID and fuzzy Algorithm for Sun Tracker Based on Tetrahedron Geometry Sensor," in *Proceedings - 2nd 2018 International Conference on Electrical Engineering and Informatics, ICELTICs 2018*, pp. 40–44, Sep. 2018, doi: 10.1109/ICELTICS.2018.8548837.
[16] L. V. Thang, Z. M. Naing, N. X. Cuong, L. D. Hieu, and S. Anatolii, "Research of solar tracking controller for PV panel based on fuzzy logic control," in *2021 IEEE Conference of Russian Young Researchers in Electrical and Electronic Engineering (ElConRus)*, pp. 2696–2699, Jan. 2021, doi: 10.1109/ElConRus51938.2021.9396105.
[17] C. H. Huang, H. Y. Pan, and K. C. Lin, "Development of intelligent fuzzy controller for a two-axis solar tracking system," *Applied Sciences*, vol. 6, no. 5, p. 130, May 2016, doi: 10.3390/app6050130.
[18] N. M. Yahya, N. Elias, and M. H. M. Nordin, "A comparison of type 1 and type 2 fuzzy logic controller for DC motor system," *Singapore: Springer Nature*, vol. 900, pp. 125–133, 2022, doi: 10.1007/978-981-19-2095-0_12.
[19] N. N. Karnik and J. M. Mendel, "Introduction to type-2 fuzzy logic systems," in *1998 IEEE International Conference on Fuzzy Systems Proceedings - IEEE World Congress on Computational Intelligence*, vol. 2, pp. 915–920, 1998, doi: 10.1109/FUZZY.1998.686240.
[20] N. N. Karnik, J. M. Mendel, and Q. Liang, "Type-2 fuzzy logic systems," *IEEE Transactions on Fuzzy Systems*, vol. 7, no. 6, pp. 643–658, 1999, doi: 10.1109/91.811231.
[21] A. Sedigh, M.-R. Akbarzadeh-T, and R. E. Tomlinson, "Comparison of type-1 and type-2 fuzzy systems for mineralization of bioprinted bone," *bioRxiv*, p. 2021.03.31.437908, 2021, [Online]. Available: https://doi.org/10.1101/2021.03.31.437908
[22] A. S. Jokandan, A. Khosravi, and S. Nahavandi, "Performance comparison of type-1 and type-2 neuro-fuzzy controllers for a flexible joint manipulator," *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, vol. 11953 LNCS, pp. 621–632, 2019, doi: 10.1007/978-3-030-36708-4_51.
[23] D. Wu, "Two differences between interval type-2 and type-1 fuzzy logic controllers: adaptiveness and novelty," in *Studies in Fuzziness and Soft Computing*, vol. 301, pp. 33–48, 2013, doi: 10.1007/978-1-4614-6666-6_3.
[24] O. Castillo, P. Melin, J. Kacprzyk, and W. Pedrycz, "Type-2 fuzzy logic: theory and applications," in *2007 IEEE International Conference on Granular Computing (GRC 2007)*, pp. 145–145, Nov. 2008, doi: 10.1109/grc.2007.118.
[25] J. M. Mendel, "Uncertainty, type-2 fuzzy sets, and footprints of uncertainty," in *Intelligent Systems for Information Processing: From Representation to Applications*, Elsevier, pp. 233–242, 2003, doi: 10.1016/B978-044451379-3/50019-4.

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