Modified T2FSMC approach for solar panel systems

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ABSTRACT
In this paper, we consider the control problem for solar panel systems such that the panel is perpendicular to the direction of sunlight, which is suitable for absorbing the sun’s energy efficiently. Based on the existing Type-2 Fuzzy Sliding Mode Control (T2FSMC) method, we propose a Modified T2FSMC approach in this paper, where a bisection algorithm is used to compute the normalized gain. According to simulation results, the performance of Modified T2FSMC is significantly better compared to the performance of T2FSMC and Fuzzy Sliding Mode Control (FSMC). Specifically, Modified T2FSMC has a smaller steady-state error and is more robust to disturbance compared with FSMC. Moreover, Modified T2FSMC also has a smaller steady-state error compared to T2FSMC.

1. Introduction
Indonesia is an archipelago country containing so many renewable resources. Water, wind and sunlight resources which are available in Indonesia are alternative power resources that can be optimized. Located at the equator line, it makes almost the entire area of Indonesia receive direct sunlight all of the year. It should be useful for Indonesia to maximize the renewable energy obtained from the sun’s heat. A solar panel is used to take benefit from the sun’s heat. The solar panel is a tool which can convert sunlight into electricity. The solar panel has a component to collect sunlight called collector. The collecting process will be maximized if the position is perpendicular to the sun rays. In order to maximize the produced electricity, we need to design a controller.

Because of its benefit, a lot of research papers about controlling solar panel and fuzzy-based control systems were presented. There are many control methods that are used. We will mention some of them here. Sliding Mode Control (SMC), Fuzzy Logic Control (FLC), Fuzzy Sliding Mode Control (FSMC) and Type-2 Fuzzy Sliding Mode Control (T2FSMC) were used in Mardlijah, Subiono, Surjanto, and Efprianto (2016) and Mardlijah, Soemarsono, and Rinanto (2017). Adaptive Neuro-Fuzzy Inference System (ANFIS) was used by Abadi, Imron, Mardlijah, and Noriyati (2018). Harrabi, Kharrat, Aitouche, and Souissi (2018) have applied a fuzzy approach to wind generation systems. Assawinchaichote (2014) has combined fuzzy and $\mathcal{H}_\infty$ for a class of nonlinear systems. Merheb, Noura, and Bateman (2015) have applied sliding mode theory to design a controller for a quadrotor. There are some literature that compare the performance of fuzzy-based controllers and other controllers such as Kiyak and Gol (2016) and Usta, Akyaszi, and Atlas (2011). Proportional Integral Derivative (PID) and FLC have been used by Kiyak and Gol (2016). Kiyak and Gol (2016) compared FLC with a PID controller for a single-axis solar tracking system. The result is that the energy obtained from the system using fuzzy logic for a solar tracking system was better, compared to systems that did not use using fuzzy logic. At the same time, a fuzzy controller is more robust compared to a PID controller. We also mention that Fuzzy Logic Control is better used in a solar tracking system than a PI controller as shown by Usta et al. (2011).

While FSMC is a combination of Type-1 Fuzzy and SMC (Jiang, Karimi, Kao, & Gao, 2018; Wang, Karimi, Shen, Fang, & Liu, 2018; Wang, Shen, Karimi, & Duan, 2018), another controller T2FSMC, proposed in Mardlijah, Jazdie, Widodo, and Santoso (2013), is a combination of Type-2 Fuzzy and SMC. Type-2 Fuzzy has a more complex membership structure than Type-1 Fuzzy (Castillo, 2012). More precisely, Type-2 Fuzzy has two membership functions: primary and secondary membership functions. Such structure provides an additional degree of freedom allowing to deal directly with the uncertainty (Mardlijah et al., 2013). SMC is a robust control technique which works well for both linear and nonlinear systems (Palm, Driankov, & Hellendoorn, 1997; Wang, Xia, Shen, &...
There are also some other methods on robust controller design, such as those proposed in Wu, Meng, et al. (2017), Wu, Lu, Shi, Su, and Wu (2017), Zhang and Wang (2017) and, Zhang, Zhang, and Wang (2016).

In Mardlijah et al. (2017), we have applied T2FSMC to solar panel systems. In that work, we used trial and error in computing the normalized gain. In that context, it needs a long time to compute the normalized gain. In order to address that issue, in this paper, we propose a method to determine the normalized gain and call it Modified T2FSMC. The method to compute the gain uses the bisection concept. According to simulation results, the performance of Modified T2FSMC is significantly better compared to both FSMC and T2FSMC. Modified T2FSMC has a smaller steady-state error and more robust to disturbance compared with FSMC. Compared to T2FSMC, Modified T2FSMC also has a smaller steady-state error. Finally, both Modified T2FSMC and T2FSMC are robust to disturbance.

The paper is structured as follows. Section 2 describes the modelling of solar panel systems and control design using Modified T2FSMC, which is the main contribution of this paper. Then, Section 3 discusses the control design of solar panel systems and the comparison between Modified T2FSMC and two other controllers: FSMC and T2FSMC. Finally, Section 4 concludes the work.

2. Modelling and control of solar panel systems

In this section, we first discuss the solar panel systems and their mathematical models (see Section 2.1). Then, we describe the main contribution of this paper (control design using Modified T2FSMC) in Section 2.2.

2.1. Solar panel systems

The solar panel is developed to produce renewable energy resources by converting solar rays into electricity. Scheme of a simple solar panel is shown in Figure 1.

A solar panel system works as follows. It is desirable to follow the direction of sun rays such that its position is perpendicular to sun rays. As such, the collector can absorb the sun’s energy maximally. We achieve this objective by controlling the DC motor (Golnaraghi & Kuo, 2009). Input in the form of solar rate \((\theta_i)\) is received by the sensor’s square silicon photo voltaic cells. The output of the system is the angular position of the rotor \((\theta_o)\) for rotating collector to follow the direction of sun rays (Mardlijah et al., 2016).

A solar panel model is obtained by substituting each mathematical equation of the solar panel component. The DC Motor scheme can be seen in Figure 2 (Golnaraghi & Kuo, 2009).

From Figure 2, we can derive the following equations:

\[
E_a(t) = R_a(t)i_a(t) + L_a \frac{di_a(t)}{dt} + E_b(t) \tag{1}
\]

\[
E_b(t) = K_b \omega(t) \tag{2}
\]

\[
T_m(t) = K_m i_a(t) \tag{3}
\]

\[
T_m(t) = J \frac{d\omega(t)}{dt} + B \omega(t) \tag{4}
\]

where \(E_a\) represents the voltage at the source, \(E_b\) represents the voltage at the motor, \(R_a\) represents the resistance value, \(L_a\) represents the capacitance value and \(\omega\) represents the angular velocity.

The obtained parameters (assumed to be constant) of the DC motor have been taken directly from measurement data of solar panel prototype (Mardlijah et al., 2017). Specifically, the parameters were obtained by experiment on DC motor Hosiden 21.6 V 0.6 A. Inductance (L), Capacitance (C), and Resistance (R) were directly measured with LCR meters. In order to obtain valid measurement data, the parameters were obtained by taking the average over 50 experiments. Those parameters are given in Table 1.
2.2. Control design using modified T2FSMC

Modified Type-2 Fuzzy Sliding Mode Control (T2FSMC) is an extension of T2FSMC where the normalized gain is computed using a bisection concept. Modified T2FSMC requires two inputs, namely $S_p$ and $d$. The output of Modified T2FSMC is a control law to the plant (Hsiao, Li, Lee, Chao, & Tsai, 2008). Then, the control law will be multiplied by the normalized gain. Figure 3 shows a scheme for Modified T2FSMC.

Modified T2FSMC uses a sliding surface, which is defined as follows:

$$ S = \dot{e} + \lambda e $$

where $e$ is the error, i.e. the difference between the set point and the output. The sliding surface is defined as the set of states where $S = 0$, equivalently $\dot{e} + \lambda e = 0$. The unmodelled dynamics which has frequencies greater than $\lambda$ is filtered out (Palm et al., 1997).

Control law of Modified T2FSMC is obtained from the following fuzzy rules (Hsiao et al., 2008). There are eight fuzzy sets for $S_p$, four fuzzy sets for $d$ and eight fuzzy sets for $u$. Table 2 describes the fuzzy rules for Modified T2FSMC (Palm et al., 1997). There is a fuzzy rule for each fuzzy set of $S_p$ and $d$. Thus, in total there are 32 fuzzy rules. One example of the fuzzy rules is ‘if $S_p$ is NB (negative big) and $d$ is B (big), then $u$ is PB (positive big)’. Other fuzzy rules in Table 2 can be defined similarly. The objective of the fuzzy rules is choosing a control value $u$ such that $S_p$ and $d$ go to zero through the sliding surface. This ensures that the error will go to the sliding surface and eventually the error goes to the origin, as shown in Figure 4.

Notice that the fuzzy rules require two inputs $S_p$ and $d$. Variable $S_p$ represents the distance between the state vector and the sliding surface, whereas variable $d$ denotes the distance between the normal vector of the sliding surface and the state vector (see Figure 4) (Mardlijah et al., 2016). The value of $S_p$ and $d$ can be written as follows:

$$ S_p = \frac{\dot{e} + \lambda e}{\sqrt{1 + \lambda^2}} $$

(5)

$$ d = \sqrt{|e|^2 - S_p^2} $$

(6)

Notice that we need to determine the normalized gain $K$ (see Figure 3). As stated in the Introduction, in T2FSMC, the normalized gain $K$ is obtained by trial and error. In Modified T2FSMC, the method to compute the gain is based on bisection concept. The detailed method is as follows:

![Figure 3. Scheme of modified T2FSMC.](image-url)
(1) Determine two values $K_1$ and $K_2$, such that the steady-state error (namely, the difference between the value of steady state and the reference) of $K_1$ is negative, and the steady-state error of $K_2$ is positive.

(2) Compute $K_3 = (K_1 + K_2)/2$.

(3) If the steady-state error of $K_3$ has negative error value and it is closer to the set point than $K_1$, then we update the value of $K_1$ by $K_3$. If the steady-state error of $K_3$ has positive error value and it is closer to the set point than $K_2$, then we update the value of $K_2$ by $K_3$.

(4) If the absolute value of the steady-state error $\leq$ tolerance of error, the desired gain $K$ is $K_3$ and stop the computation. Otherwise, return to Step 2.

In the method, the variables $K_1$ and $K_2$ are constant scalar values. The initial values of $K_1$ and $K_2$ are determined by trial and error. The steady-state error is obtained from the simulation, by computing the difference between the steady-state value and the desired value (or set point).

3. Results and discussions

3.1. Adaptation of modified T2FSMC to solar panel systems

In this section, we first adapt the Modified T2FSMC to solar panel systems. For comparison, we also compute FSMC and T2FSMC.

First, we determine the interval value of $S_p$, $d$ and $u$. Then, we divide the interval value of each variable into some membership functions.

From (3) and (4), we obtain

$$i_a(t) = \frac{J}{K_m} \frac{d\omega(t)}{dt} + \frac{B\omega(t)}{K_m}$$

(7)

Then we substitute (7) to (1). After performing some simple algebraic manipulation, we obtain the following equations:

$$E_a(t) = Ra \left\{ \frac{J}{K_m} \frac{d\omega(t)}{dt} + \frac{B}{K_m}\omega(t) \right\} + L_a \left\{ \frac{J}{K_m} \frac{d\omega(t)}{dt} + \frac{B}{K_m}\omega(t) \right\}$$

$$+ K_b\omega(t)$$

$$= \frac{R_a J}{K_m} \frac{d\omega(t)}{dt} + \left( \frac{R_a}{K_m} + \frac{L_a B}{K_m} \right) \frac{d\omega(t)}{dt} + \frac{L_a B}{K_m} \frac{d\omega(t)}{dt} + K_b\omega(t)$$

(8)

Then we move the term containing the second derivative of $\omega$ to the left-hand side of the equation:

$$\frac{L_a J}{K_m} \frac{d\omega(t)}{dt} = E_a(t) - \left( \frac{R_a B + K_b K_m}{K_m} \right) \omega - \left( \frac{R_a}{K_m} + L_a B \right) \frac{d\omega(t)}{dt}$$

$$\omega = \frac{K_m E_a(t)}{L_a J} - \left( \frac{R_a B + K_b K_m}{L_a J} \right) \omega - \left( \frac{R_a}{L_a J} \right) \frac{d\omega(t)}{dt}$$

Equation (8) can be simplified into

$$\dot{\omega} = Cu - D_1 \omega - D_2 \dot{\omega}$$

where

$$u = E_a, \quad C = \frac{K_m}{L_a J}, \quad D_1 = \frac{R_a B + K_b K_m}{L_a J}, \quad D_2 = \frac{R_a}{L_a J}$$

In order to obtain the set of possible values for $S_p$ and $d$, the error of the system is calculated using the formula below:

$$e = \omega - \omega_d$$

$$\dot{e} = \dot{\omega},$$

where $\omega_d$ is the desired angular velocity. We assume that the panel is able to move $180^\circ$ for 12 h. The value of $\omega_d$ is the angular distance traversed by the solar panel for each second. Thus, the value of $\omega_d$ is $7.3 \times 10^{-5}$ radian.

By observing the open-loop solar panel system, we obtain the following error interval

$$e \in [-262.7906, 262.7905]$$

$$\dot{e} \in [226.3062, 226.3062].$$

The interval values of $e$ and $\dot{e}$ are then substituted into (5) and (6) to compute the interval values of $S_p$ and $d$ as follows:

$$S_p \in [-261.4845, 261.4845],$$

$$d \in [0, 225.2].$$

On the other hand, the interval of $u$ is obtained from the voltage which works on the DC motor as follows:

$$u \in [-12, 12].$$

For the FSMC controller, we use membership functions shown in Figures 5–7. Furthermore, Figures 8–10 illustrate the membership functions of T2FSMC and Modified T2FSMC. The advantage of membership function for
T2FSMC and Modified T2FSMC compared with FSMC is that the former can handle more general uncertainties because the membership function is constructed by intervals. The membership functions of $S_p$, $d$ and $u$ for FSMC, T2FSMC and Modified T2FSMC are obtained by dividing the interval value into some membership functions of equal size. The interval value of $S_p$ and $u$ are divided into eight membership functions, whereas the interval value of $d$ is divided into four membership functions. The primary and secondary membership functions in Figure 8 is obtained by adding and subtracting the membership function in Figure 5 by 5%. We also do the same for other membership functions.

3.2. Simulations
In this subsection, we compare the performance of FSMC, T2FSMC and Modified T2FSMC. In Section 3.2.1, we compare the performance of FSMC and Modified T2FSMC. Then the performance of T2FSMC and Modified T2FSMC is discussed in Section 3.2.2. In these simulations, the initial values for $\omega$ and $\dot{\omega}$ are 0.000073 and 0, respectively. Furthermore, we choose $\lambda = 10$. 

Figure 5. Fuzzy membership function of $S_p$.

Figure 6. Fuzzy membership function of $d$.

Figure 7. Fuzzy membership function of $u$.

Figure 8. Type-2 fuzzy membership function of $S_p$.

Figure 9. Type-2 fuzzy membership function of $d$.

Figure 10. Type-2 fuzzy membership function of $u$. 
3.2.1. Comparison between FSMC and modified T2FSMC

We compare the performance of FSMC and Modified T2FSMC in three scenarios. In the first scenario, there is no disturbance. In the second scenario, there is an impulse disturbance. Finally, in the third scenario, there is a sinusoidal disturbance.

In the first scenario, Modified T2FSMC and FSMC are simulated without any disturbance. The simulation results showed that the normalized gain for FSMC was 1400, and the normalized gain for Modified T2FSMC was 0.00012645. The result is shown in Figure 11. In the simulation, FSMC has a better performance compared with the Modified T2FSMC: FSMC needs 0.68 s to reach the steady state, whereas Modified T2FSMC needs 4.594 s to reach the steady state. On the other hand, the steady-state error of Modified T2FSMC is significantly smaller compared to FSMC. The error of FSMC is approximately ± 2% of the set point. In summary, Modified T2FSMC has a smaller steady-state error, although FSMC may have better rise-time performance.

In order to compare the robustness, impulse and sinusoidal disturbances are given to the system controlled by Modified T2FSMC and FSMC. Impulse signal is a
signal appearing at a short time period. It represents a disturbance in a short duration from outside the system. The impulse signal disturbance is given at 10 s after the simulation is started. As we can see in Figure 12, FSMC needs a longer time to reach the set point after the disturbance occurs: FSMC needs almost 1 s whereas Modified T2FSMC needs less than 0.1 s.

In the second case, sinusoidal disturbance with amplitude $10^{-7}$ and frequency 1 is given to the control system. In other words, the disturbance signal is $d(t) = 10^{-7} \sin(\pi t/2)$. Sinusoidal disturbance represents a periodic disturbance that appears all the time. Figure 13 shows that FSMC cannot handle the effect of disturbance in the long term, but Modified T2FSMC is able to handle it properly.

### 3.2.2. Comparison between modified T2FSMC and T2FSMC

In this section, we compare the performance of T2FSMC and Modified T2FSMC. We try two gains for T2FSMC, namely 0.001 and 0.0001. For Modified T2FSMC, the normalized gain is 0.00012645, which is obtained from the procedure in Section 2.2. We have conducted three scenarios: disturbance-free case, impulse disturbance and
sinusoidal disturbance. The simulation results for the disturbance-free case is depicted in Figure 14. As we can see from the figure, the steady-state error of Modified T2FSMC is significantly smaller compared to the steady-state error of T2FSMC. The steady-state error of T2FSMC for $K = 0.001$ and $K = 0.0001$ is $5.023 \times 10^{-4}$ and $1.547 \times 10^{-5}$, respectively. For Modified T2FSMC, the steady-state error is $5.711 \times 10^{-6}$.

The simulation of Modified T2FSMC and T2FSMC for impulse disturbance and sinusoidal disturbance is displayed in Figures 15 and 16, respectively. As we can see from these figures, both Modified T2FSMC and T2FSMC are able to handle impulse and sinusoidal disturbances. Similar to the observation results for the disturbance-free case, Modified T2FSMC has a significantly smaller steady-state error compared to the T2FSMC.

4. Conclusion

This paper has proposed Modified Type-2 Fuzzy Sliding Mode Control (Modified T2FSMC) for solar panel systems. In the literature, the normalized gain is determined by trial and error. In this paper, we used Modified T2FSMC, where the normalized gain is computed using a method based on bisection concept. Then we designed in detail the controller using Modified T2FSMC. The overall mean absolute error of Modified T2FSMC is $5.7117 \times 10^{-6}$, which is acceptable. For comparison, we also
design controllers using Type-2 Fuzzy Sliding Mode Control (T2FSMC) and Fuzzy Sliding Mode Control (FSMC). According to the simulation results, the Modified T2FSMC has smaller steady-state error and is more robust compared to FSMC. Furthermore, Modified T2FSMC has smaller steady-state error compared to T2FSMC. In our simulations, the steady-state error of T2FSMC is approximately 2.7 times larger than the error of Modified T2FSMC.

In the future, we are planning to remove the assumption that all states are measured. In this case, we may use some filtering techniques to estimate the unmeasured states, as in Jiang, Zhang, Karimi, Lin, and Song (2018). Furthermore, we are also developing the proposed method to employ some optimization algorithms based on artificial intelligence.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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