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Article

Interval Type-II Fuzzy Rule-Based STATCOM for Voltage Regulation in the Power System

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Abstract: The static synchronous compensator (STATCOM) has recently received much attention owing to its ability to stabilize power systems and mitigate voltage variations. This paper investigates a novel interval type-II fuzzy rule-based PID (proportional-integral-derivative) controller for the STATCOM to mitigate bus voltage variations caused by large changes in load and the intermittent generation of photovoltaic (PV) arrays. The proposed interval type-II fuzzy rule base utilizes the output of the PID controller to tune the signal applied to the STATCOM. The rules involve upper and lower membership functions that ensure the stable responses of the controlled system. The proposed method is implemented using the NEPLAN software package and MATLAB/Simulink with co-simulation. A six-bus system is used to show the effectiveness of the proposed method. Comparative studies show that the proposed method is superior to traditional PID and type-I fuzzy rule-based methods.

Keywords: photovoltaic array; interval type II fuzzy rule; STATCOM; voltage variation

1. Introduction

A static synchronous compensator (STATCOM) is a volt-ampere-reactive (VAR)/voltage regulation device that is used in both electric transmission and distribution networks. The STATCOM utilizes a voltage- or current-source converter and can act as either a source or sink of reactive power in the power system. If the STATCOM is connected to a source of power, it can also provide the real power.

Traditionally, STATCOMs have been used to study the stability problem. Wang and Hsiung presented a STATCOM control scheme to enhance the damping of a grid-connected 80 MW offshore wind farm and 40 MW marine-current farm [1]. The damping controller was designed using modal control theory and has been examined under different operating conditions. Wang and Truong presented a damping controller of the STATCOM by using a pole-assignment approach to ensure adequate damping of the dominant modes of the studied power system [2]. Beza and Bongiorno presented an adaptive power oscillation damping controller for a STATCOM equipped with an energy storage device [3]; this was achieved using a signal estimation technique based on a modified recursive least-square algorithm, which supported the adaptive estimation of low-frequency electromechanical oscillations from locally-measured signals during power system disturbances.

Recently, STATCOMs have been also used to deal with the voltage problems in the power system. Wang and Crow developed a feedback linearization controller to regulate bus voltages [4]. Chen *et al.* investigated the use of a STATCOM for system voltage control, during peak solar irradiation, in order to increase the PV installation capacity of a distribution feeder and avoid the voltage violation problem [5]. Aziz *et al.* presented a method for VAR planning with a STATCOM for an industrial system that comprised multiple distributed generation units. The impact of the placement of STATCOM on voltage recovery and the rating of the STATCOM were determined through time-domain simulations [6]. Xu and Li proposed an adaptive PI control, which can self-adjust the control gains in response to a disturbance such that the desired response is maintained, regardless of any change in the operating conditions [7].

On the other hand, conventional fuzzy rules (also called a type-I (T1) fuzzy logic system) have been used to design controllers and have been found to be effective when the controlled plant is not complex. On the contrary, an interval type-II (IT2) fuzzy logic system outperforms T1 if the system is complex. Zadeh introduced the concept of type-II fuzzy sets, as an extension of type-I fuzzy sets, incorporating an additional dimension that represents uncertainty in degrees of membership [8]. Liang and Mendel proposed a simplified method to compute the input and antecedent operations for IT2 fuzzy logic systems [9]. They showed that all of the results that are needed to implement an IT2 fuzzy logic system can be obtained using T1 fuzzy logic mathematics [10]. Other works have elaborated IT2 fuzzy logic systems, such as [11–14]. A tutorial about IT2 fuzzy logic systems is also available in [15].

Recently, the IT2 fuzzy logic system was applied to solve power system problems. Tripathy and Mishra proposed an IT2 fuzzy logic-based thyristor-controlled series capacitor to improve power system stability. They used the concept of uncertainty bounds for type-reduction to overcome the limitation of the time-consuming iterative method generally used for type reduction [16]. Khosravi *et al.* proposed the application of IT2 fuzzy logic systems to the problem of short-term load forecasting [17]. Mikkili and Panda proposed a shunt active filter to improve the power quality of the electrical network by mitigating the harmonics with the help of T1 and IT2 fuzzy logic controllers [18]. Jafarzadeh *et al.*, proposed T1 and IT2 Takagi-Sugeno-Kang (TSK) fuzzy systems for both modeling and prediction of solar power [19]. Khosravi and Nahavandi used IT2 fuzzy logic systems for day-ahead load forecasting, which introduced an optimal type reduction algorithm to improve the approximation [20]. Murthy *et al.* addressed that the failure rate and the repair rate of any component of a power system for reliability studies are uncertain; therefore, a membership representation using precise and crisp functions seems practically unreasonable [21].

In this work, IT2 fuzzy rules are applied to the STATCOM to mitigate voltage variations caused by large load changes and intermittent photovoltaic power. The proposed IT2 fuzzy rule-based STATCOM is more robust than those described elsewhere [4–7]. The proposed method is implemented by integrating the NEPLAN software package with MATLAB/Simulink. The NEPLAN software package is utilized to perform a dynamic power flow simulation while MATLAB/Simulink is used to design the IT2 fuzzy rule-based controller and STATCOM.

The rest of this paper is organized as follows. Section 2 provides the background of IT2 fuzzy logic systems. Section 3 presents the method based on the IT2 fuzzy rule base for mitigating the voltage variations in the power system. Section 4 summarizes the simulation results of a six-bus distribution system with PV generation. The conclusions are presented in Section 5.

2. Background of IT2 Fuzzy Logic Systems

2.1. IT2 Fuzzy Sets

A traditional type 1 (T1) fuzzy set Ã in X is defined as a set of ordered pairs, as follows.

$$\tilde{A} = \{(x, \mu_{\tilde{A}}(x)) \mid x \in X\} \quad (1)$$

where X is the universal set and $\mu_{\tilde{A}}(x)$ is the membership function (MF) of x in Ã. Notably, the MF represents the degree to which x belongs to Ã and the value of MF is normally between zero and unity. A high value of the MF indicates that x is very likely to be in Ã. Figure 1a shows an example of a T1 fuzzy set, Ã. Any number in the x domain corresponds to a membership value. The MF $\mu_{\tilde{A}}(x)$ of a T1 fuzzy set can be chosen either based on the user's experience or using algorithms.

A traditional T1 fuzzy set is certain in the sense that its membership values are crisp. In contrast, the type II fuzzy set is characterized by MFs that are themselves fuzzy. The IT2 fuzzy set is a special case of type II fuzzy sets. Figure 1b shows an example of an IT2 fuzzy set. The membership value of an IT2 fuzzy set lies within an interval. An IT2 fuzzy set is bounded by two type-1 MFs, $\bar{A}$ and $\underline{A}$, which are referred to as upper MF (UMF) and lower MF (LMF), respectively. The area between $\bar{A}$ and $\underline{A}$ is called the footprint of uncertainty (FOU). IT2 fuzzy sets are particularly useful when specifying exact MFs is difficult.

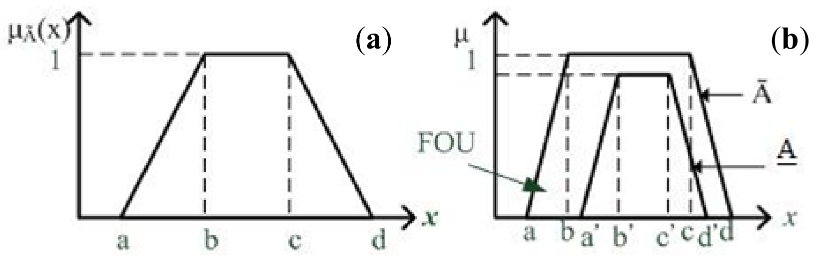


Figure 1. Examples of (**a**) a T1 membership function; (**b**) IT2 membership functions (UMF $\bar{A}$ and LMF $\underline{A}$).

2.2. IT2 Fuzzy Rules

Figure 2 shows a schematic diagram of an IT2 fuzzy logic system. The outputs of the inference engine are IT2 fuzzy sets. A type-reducer is needed to convert IT2 fuzzy sets into a T1 fuzzy set before defuzzification is carried out.

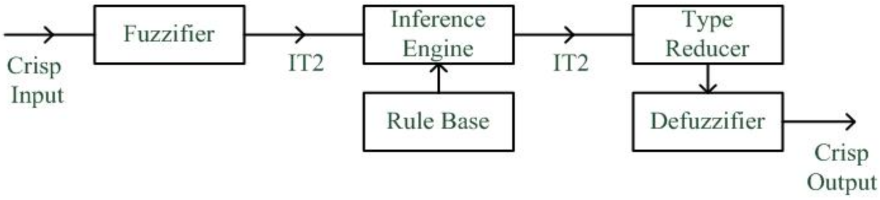


Figure 2. IT2 fuzzy logic system.

Consider N IT2 fuzzy rules. The *n*th rule can be expressed as follows.

IF x_1 is $\tilde{A}_{1n}$ and … and x_M is $\tilde{A}_{Mn}$ then y is Y_n. $n = 1, 2, \ldots, N$.

Where $\tilde{A}_{in}$ (i =1, 2, …, M) are IT2 fuzzy sets and $Y_n=[\underline{y}_n, \overline{y}_n]$ is an interval. Assume that the input vector $x^* = (x_1^*, x_2^*, \ldots, x_M^*)$. The IT2 fuzzy reasoning can be implemented using the following steps [22].

(1) Evaluate the membership of x^* on each $\tilde{A}_{in}$, $[\mu_{\underline{A}_{in}}(x_i^*), \mu_{\bar{A}_{in}}(x_i^*)]$, $i = 1, 2, \ldots, M$, $n = 1, 2, \ldots, N$.

(2) Evaluate the firing interval of the *n*th rule, $F_n(x^*) \equiv [\underline{f}_n, \overline{f}_n]$, $n = 1, 2, \ldots, N$.

$$[\underline{f}_n, \overline{f}_n] = [\mu_{\underline{A}_{1n}}(x_1^*) \times \ldots \times \mu_{\underline{A}_{Mn}}(x_M^*), \mu_{\bar{A}_{1n}}(x_1^*) \times \ldots \times \mu_{\bar{A}_{Mn}}(x_M^*)] \tag{2}$$

(3) Conduct type reduction using $F_n(x^*)$ and $[\underline{y}_n, \overline{y}_n]$.

$$y_\ell = \min_{j \in [1, N-1]} \frac{\sum_{n=1}^{j} \overline{f}_n \underline{y}_n + \sum_{n=j+1}^{N} \underline{f}_n \underline{y}_n}{\sum_{n=1}^{j} \overline{f}_n + \sum_{n=j+1}^{N} \underline{f}_n} \tag{3}$$

$$y_\ell = \min_{j \in [1, N-1]} \frac{\sum_{n=1}^{j} \underline{f}_n \overline{y}_n + \sum_{n=j+1}^{N} \overline{f}_n \overline{y}_n}{\sum_{n=1}^{j} \underline{f}_n + \sum_{n=j+1}^{N} \overline{f}_n} \tag{4}$$

The sets $\{\underline{y}_n\}$ and $\{\overline{y}_n\}$ are sorted in ascending order. The values of y_ℓ and y_r in Equations (3) and (4) can be evaluated using Karnik-Mendel algorithms [23].

(4) Estimate the defuzzified output.

$$y = \frac{y_\ell + y_r}{2} \tag{5}$$

3. Proposed Method

A STATCOM can be operated with either current source or voltage source converters; the latter are the more popular. Essentially, the main function of the STATCOM is to regulate voltages by reactive power control unless an additional energy storage system is connected to the DC bus of the STATCOM. Figure 3 illustrates the model of the STATCOM that is used herein [1,2].

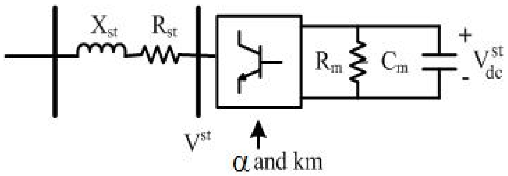


Figure 3. Model of static synchronous compensator (STATCOM).

The DC voltage V_{dc}^{st} can be transformed to be the *d*- and *q*-axis components of the output terminal of the STATCOM as follows [1,2].

$$V_d^{st} = V_{dc}^{st} \times km \times \sin(\theta_{bus} + \alpha) \tag{6}$$

$$V_q^{st} = V_{dc}^{st} \times km \times \cos(\theta_{bus} + \alpha) \tag{7}$$

where θ_{bus} and V_{dc}^{st} denote the phase angle of the controlled AC bus and the DC voltage across the DC capacitance C_m, respectively The variables km and α are the modulation index and the phase angle of the STATCOM, respectively. From Figure 3, one can obtain Equations (8) and (9) as follows [1,2].

$$C_m \frac{d}{dt} V_{dc}^{st} = \omega_b \left(I_{dc}^{st} - \frac{V_{dc}^{st}}{R_m} \right) \tag{8}$$

$$I_{dc}^{st} = i_q^{st} km \cos(\theta_{bus} + \alpha) + i_d^{st} km \sin(\theta_{bus} + \alpha) \tag{9}$$

where I_{dc}^{st} is the DC current that flows into the positive terminal of V_{dc}^{st}. R_m is the equivalent resistance of the STATCOM. i_d^{st} and i_q^{st} are the *d*- and *q*-axis currents that flow into the terminals of the STATCOM, respectively.

3.1. Dynamic Equations of STATCOM

Let V^{st} be the voltage at the STATCOM and Vd_{bus} and Vq_{bus} be the voltages of the *d*- and *q*-axes at the controlled AC bus, respectively. From the model of the STATCOM, the following dynamic equations are attained. Let the controlled bus voltage magnitude be Vt = $\sqrt{Vd_{bus}^2 + Vq_{bus}^2}$. The following dynamic equations can be obtained:

$$\frac{d}{dt} V^{st} = \frac{km}{C_m} \left(\frac{i_q^{st} Vq_{bus}}{Vt} \cos\alpha + \frac{i_q^{st} Vd_{bus}}{Vt} \sin\alpha \right) + \frac{km}{C_m} \left(\frac{i_d^{st} Vd_{bus}}{Vt} \cos\alpha + \frac{i_d^{st} Vq_{bus}}{Vt} \sin\alpha \right) - \frac{V^{st}}{C_m R_m} \tag{10}$$

$$\frac{d}{dt} \alpha = \left(Kc \times \left(V_{ref} - Vt \right) - \alpha \right) \times \frac{1}{Tc} \tag{11}$$

where Kc and Tc are parameters of the transfer function between Δα and ΔV_{dc}^{st}. V_{ref} is a given voltage reference.

$$\frac{d}{dt} km = \left(Ks \times \left(V^{st} - \sqrt{2} \right) - km \right) \times \frac{1}{Ts} \tag{12}$$

where Ks and Ts are parameters of the transfer function between Δkm and ΔVt

$$\frac{d}{dt}i_d^{st} = \left(Vd_{bus} - R_{st} \times i_d^{st} + i_q^{st} \times X_{st} - km \times V^{st} \left(\frac{Vd_{bus}}{Vt}\cos\alpha + \frac{Vq_{bus}}{Vt}\sin\alpha \right) \right) \times \frac{1}{X_{st}} \tag{13}$$

$$\frac{d}{dt}i_q^{st} = \left(Vq_{bus} - R_{st} \times i_q^{st} + i_d^{st} \times X_{st} - km \times V^{st} \left(\frac{Vq_{bus}}{Vt}\cos\alpha + \frac{Vd_{bus}}{Vt}\sin\alpha \right) \right) \times \frac{1}{X_{st}} \tag{14}$$

The dynamic phenomenon in the power system can be studied using the above dynamic equations, the swing equations of synchronous machines, and network equations.

3.2. IT2 Fuzzy Rules for Controllers

This paper proposes an IT2 fuzzy rule-based controller for mitigating the voltage variation, as shown in Figure 4. The term $V_{ref} - Vt$ in Equation (11) will be replaced by the output (modified ΔVt) of the IT2 fuzzy rule base. The proposed IT2 fuzzy rule is expressed as

IF x_1 is $\tilde{A}_{1n}$ and x_2 is $\tilde{A}_{2n}$ then y is Y_n. $n = 1, 2, \ldots, 25$.

where x_1 is the output of the PID controller (denoted as ΔV_t') and x_2 is the change rate of ΔV_t'. The variable y is the modified ΔVt, which replaces the term $V_{ref} - Vt$ in Equation (11).

A total of 25 IT2 fuzzy rules are implemented in the proposed method (*i.e.*, N = 25), as shown Table 1. The symbols NB, NS, ZR, PS, PB, IB, IS, KV, DS, DB, represent "Negative Big", "Negative Small", "Zero", "Positive Small", "Positive Big", "Increasing and Big", "Increasing and Small", "Keeping Value", "Decreasing and Small", and "Decreasing and Big", respectively. All UMF and LMF of $\tilde{A}_{1n}$ and $\tilde{A}_{2n}$ are expressed as trapezoid functions. Possible conditions of x_1 and x_2 could be NB, NS, ZR, PS or PB and the consequent actions y could be IB, IS, KV, DS or DB, as shown in Table 1.

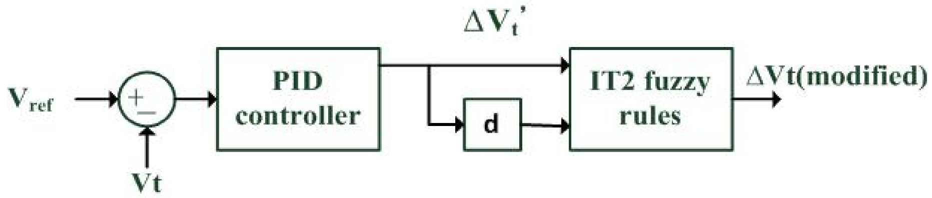


Figure 4. IT2 fuzzy rule-based controller. (Symbol "d" means "derivative")

Table 1. Twenty-five IT2 fuzzy rules.

Linguistic Variables of x_1 and x_2	x_1 = NB	x_1 = NS	x_1 = ZR	x_1 = PS	x_1 = PB
x_2 = PB	KV	IS	IB	IB	IB
x_2 = PS	DS	KV	IS	IB	IB
x_2 = ZR	DB	DS	KV	IS	IB
x_2 = NS	DB	DB	DS	KV	IS
x_2 = NB	DB	DB	DB	DS	KV

Notes: Negative Big (NB), Negative Small (NS), Zero (ZR), Positive Small (PS), Positive Big (PB), Increasing and Big (IB), Increasing and Small (IS), Keeping Value (KV), Decreasing and Small (DS), Decreasing and Big (DB).

3.3. Co-Simulation between NEPLAN and SIMULINK

Two software packages, namely NEPLAN [24] and MATLAB/Simulink (MathWorks, Natick, MA, USA), are used to implement the proposed method. The NEPLAN software package deals with the dynamic power flow simulation while the IT2 fuzzy rule-based controller and STATCOM are modeled by MATLAB/Simulink, as shown in Figure 5.

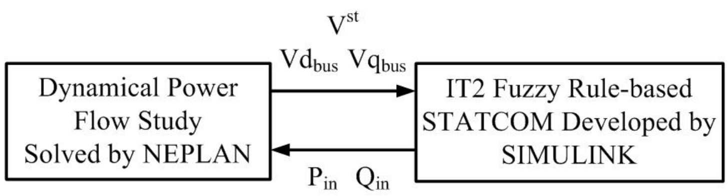


Figure 5. Co-simulation conducted by integrating NEPLAN with Simulink.

The NEPLAN software package has interfaces for linking with Simulink. The dynamic power flow studies performed in the NEPLAN package are conducted by running a power flow program with varying real and reactive power injections (P_{in} and Q_{in}). A constant time step for running the power flow program is specified in the NEPLAN package. V^{st}, Vd_{bus}, and Vq_{bus}, computed by the NEPLAN package, are fed to Simulink.

3.4. Discussions of the Proposed Method

Two comments about the proposed method are discussed as follows:

(1) The proposed method utilized 25 IT2 fuzzy rules to implement the STATCOM controllers. In power system problems many facilities require controllers, which may be realized by different types of fuzzy rules, to stabilize the power system. Table 2 summarizes eight fuzzy rule-based controllers with their corresponding problems, number of fuzzy rules, types of fuzzy rules, and hardware [25–32]. It can be found that the numbers of fuzzy rules are in the range of 16–60. The state-of-the-art DSP chip or CPU is able to accommodate these numbers of fuzzy rules and provide fast calculation for controlling the kW- or MW-scaled facilities in the power system.

(2) The existing STATCOM works, such as References [4–7] mentioned in Section 1, have the following limitations and are less robust than the proposed method. (i) The work of Wang and Crow in [4] needs to linearize the nonlinear system before applying the feedback linearization transformation. The state feedback matrix needs to be determined by linear control techniques, such as pole assignment. As described in [4], when an operating point crosses the singular surface of the power system problem, the system matrix becomes ill-conditioned and the trajectory curves are more likely to oscillate dramatically near this point. This may cause unexpected uncontrollability and chaotic behavior in the STATCOM dynamics. (ii) All the control gains in Chen's work [5] are fixed and not adaptive to a change of scenarios. (iii) Aziz's work in [6] addressed the application of STATCOM at the planning stage. Aziz tuned the PID parameters by taking the step response of the open-loop plant into consideration. The results were verified in the peak load condition only. (iv) The work of Xu and Li lies in three essential parameters: allowed delayed time of response and ideal ratio of K_p over K_i for both current and voltage control loops, where K_p and K_i denote the parameters of proportional and

integral gains, respectively. Actually, the "ideal ratio" of K_p over K_i is not well-defined and may depend on the operating conditions of different power systems.

Table 2. Eight fuzzy rule-based controllers and their corresponding features.

Problems	Number of Fuzzy Rules	Types of Fuzzy Rules	Hardware	References
Maximum power-point tracker for photovoltaic arrays	16	Mamdani	Infineon TriCore TC1796	[25]
Design of wide-area damping controller to damp the inter-area oscillations	30	Mamdani	-	[26]
Improvement of transient stability using FACTS devices	30	Mamdani	-	[27]
Improvement of transient stability using bang-bang controller	49	Mamdani	-	[28]
Control of the inverter for utilization of the wind energy	49	Mamdani	PC with DT2821 Data Card	[29]
Design of power system stabilizer	49	Mamdani	-	[30]
Design of power system stabilizer	49	Mamdani	-	[31]
Power management of energy of storage systems	60	Takagi-Sugeno	DSP TMS320F2812	[32]

4. Simulation Results

A six-bus power system, as shown in Figure 6, is studied. The PV farm with a generating capacity of 6.3 MW is located at bus 6. An IT2 rule-based STATCOM is located at bus 4. For comparison, the performance obtained by the traditional fuzzy rule-based (Type I) STATCOM is also provided herein. The values of K_p, K_i and K_d in Figure 4 are 10, 10 and 0, respectively. Suppose that the variation of irradiation is linear. The MVA base is 100. The Appendix provides the parameters of IT2 fuzzy rules as well as parameters of the STATCOM model.

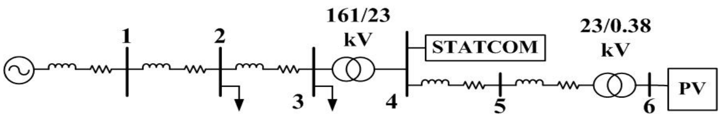


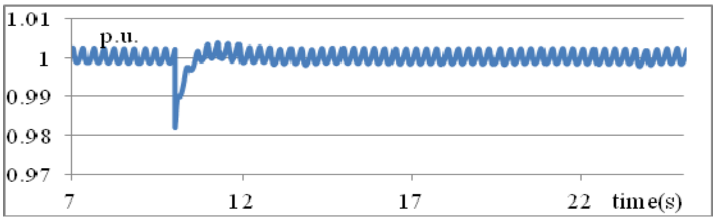
Figure 6. Studied system.

4.1. Scenario 1: Switching a Heavy Load

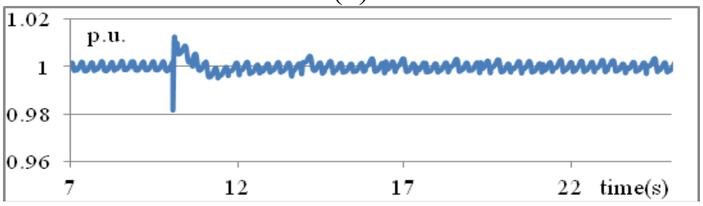
The demands of buses 2 and 3 are 30 MW + j20 MVAR and 100 MW + j30 MVAR, respectively. At t = 10 s, an additional heavy load 60 MW + j60 MVAR is switched on at bus 3. The irradiation in this scenario is zero.

Figure 7 shows the controlled voltage at bus 3 obtained using three different methods—traditional PID, T1 fuzzy rules, and IT2 fuzzy rules. As shown in Figure 7a, the voltage drops at 10 s and recovers slowly when traditional PID control is used. The steady-state voltage is still oscillating. When T1 fuzzy rules are used, the voltage recovers quickly after dropping but an overshoot occurs, as shown in

Figure 7b. Again, the steady-state voltage is still oscillating. When the proposed IT2 fuzzy rules are used, the rising time and overshoot of the voltage are almost negligible, as shown in Figure 7c.



(**a**)



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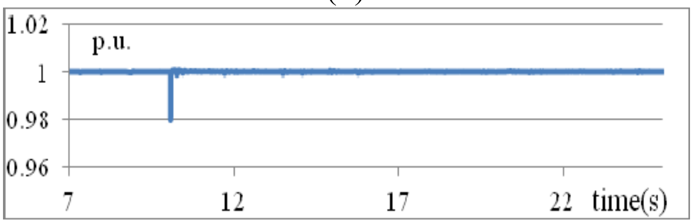
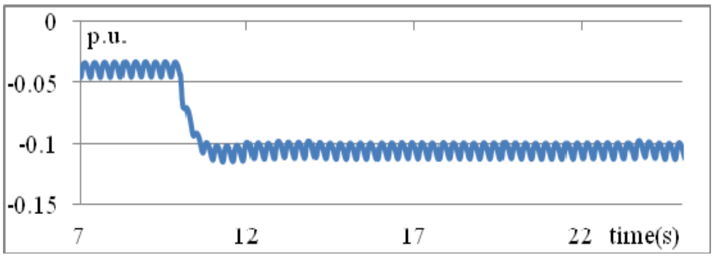


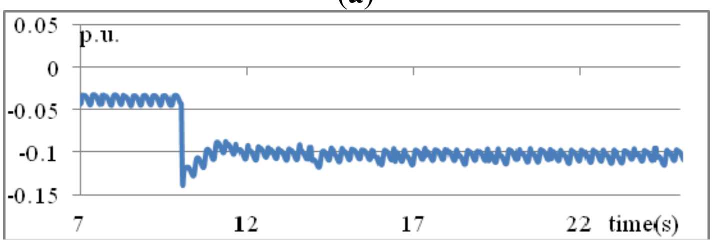
(**c**)

Figure 7. Voltages at bus 3 obtained using three methods: (**a**) traditional PID; (**b**) T1 fuzzy rules; (**c**) IT2 fuzzy rules (Scenario 1).

Figure 8 illustrates the reactive power injection from the STATCOM obtained using the three methods. The variations of voltages, shown in Figure 7, are consistent with those of the reactive powers shown in Figure 8.

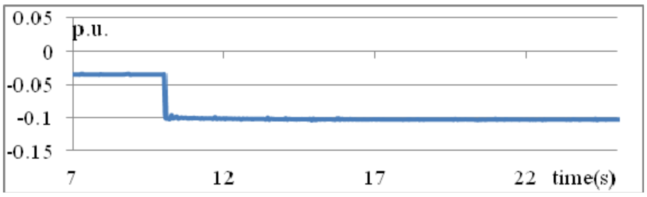


(**a**)



(**b**)

Figure 8. *Cont.*



(**c**)

Figure 8. MVARs from STATCOM obtained using three methods: (**a**) traditional PID; (**b**) T1 fuzzy rules; (**c**) IT2 fuzzy rules (Scenario 1).

4.2. Scenario 2: Increasing and then Decreasing Irradiations

The loads at buses 2 and 3 are 30 MW + j20 MVAR and 10 MW + j3 MVAR, respectively. The irradiation changes linearly. Initially, the MW generation from the PV is 0.063 p.u., as shown in Figure 9. The MW generation starts to decrease at t = 17 s and becomes 0.0363 p.u. at t = 21 s.

Figure 10 shows the controlled voltage at bus 3 obtained using three methods—traditional PID, T1 fuzzy rules, and IT2 fuzzy rules. As shown in Figure 10a, the voltage decreases slightly near t = 18 s and increases back to the nominal value near t = 21 s. The proposed IT2 fuzzy rules yield the best voltage performance, as shown in Figure 10c.

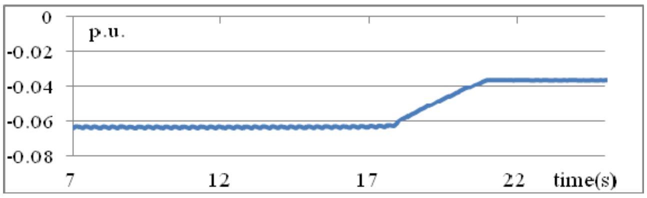
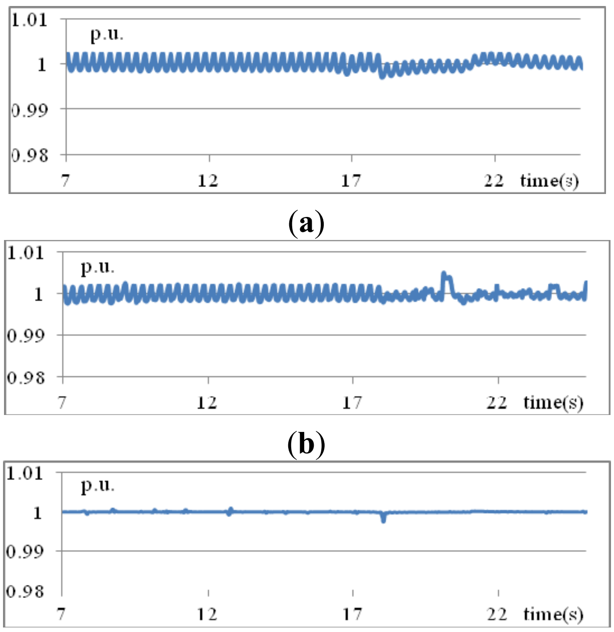


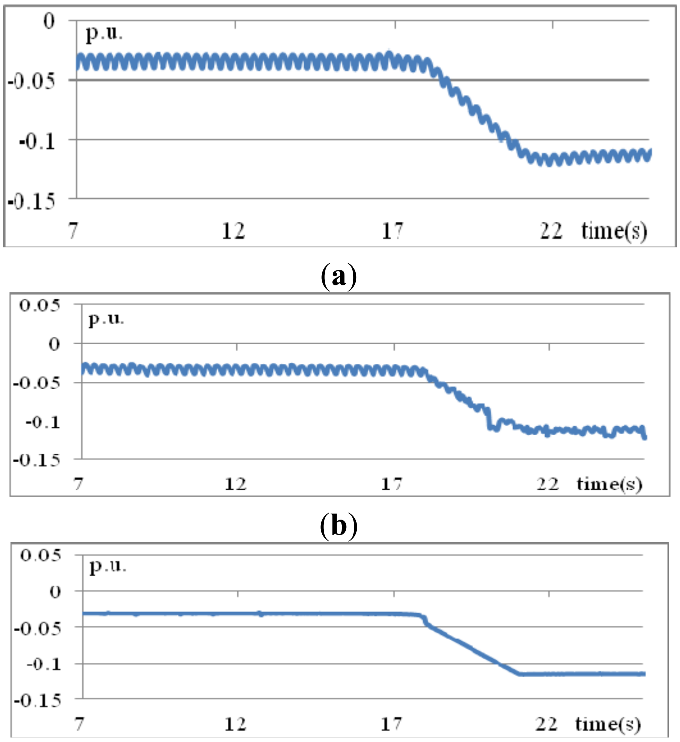
Figure 9. Variations of MW generation from PV (Scenario 2).



(**c**)

Figure 10. Voltages at bus 3 obtained using three methods: (**a**) traditional PID; (**b**) T1 fuzzy rules; and (**c**) IT2 fuzzy rules (Scenario 2).

The MVAR injections from the STATCOM increase from 0.031 p.u. close to t = 17 s to 0.114 p.u. near t = 21 s, as shown in Figure 11. Of the three methods, the proposed IT2 fuzzy rule- based method performs best.



(**a**) (**b**) (**c**)

Figure 11. MVARs from STATCOM obtained using three methods: (**a**) traditional PID; (**b**) T1 fuzzy rules; and (**c**) IT2 fuzzy rules (Scenario 2).

4.3. Scenario 3: Varying Irradiations

Buses 2 and 3 have demands of 30 MW + j20 MVAR and 10 MW + j3 MVAR, respectively. The irradiation is 1000 W/m^2 at t = 0 s. The irradiation increases to 1400 W/m^2 at t = 10, and thereafter linearly changes to be 1000, 1400, and 1000 W/m^2 at t = 12, 15 and 18 s, respectively, in the third scenario. The variations of MW generations from PV are shown in Figure 12.

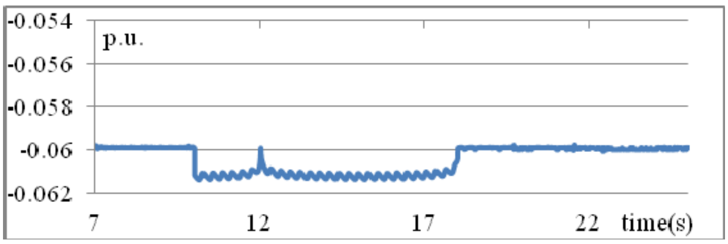


Figure 12. Variations of MW generations from PV (Scenario 3).

Figures 13 and 14 plot the controlled voltages and MVAR from the STATCOM, respectively. It can be found that the proposed IT2 fuzzy rule-based method always acquire the most stable performance than traditional PID and T1 fuzzy rule-based methods.

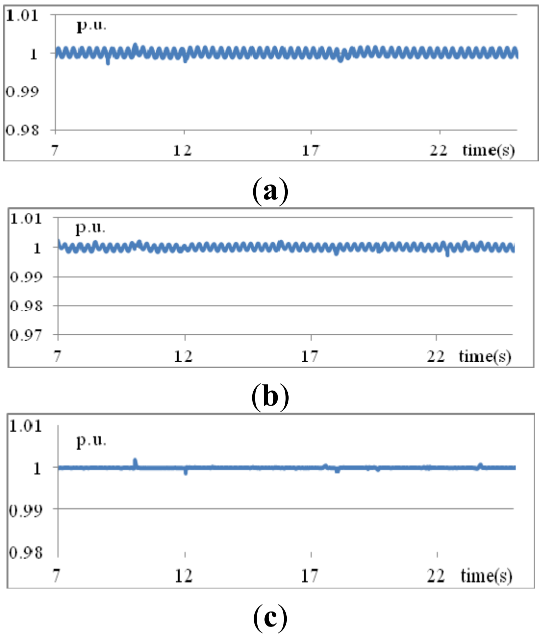


Figure 13. Voltages at bus 3 using obtained three methods: (**a**) traditional PID; (**b**) T1 fuzzy rules; (**c**) IT2 fuzzy rules (Scenario 3).

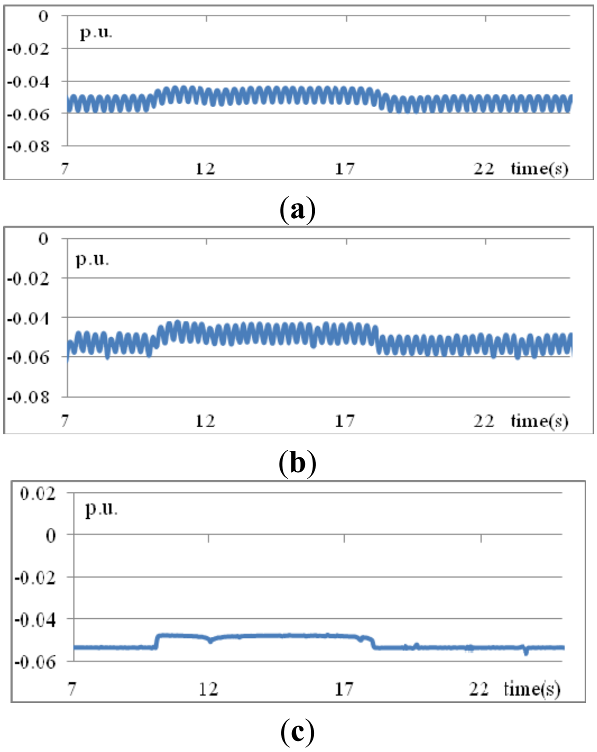
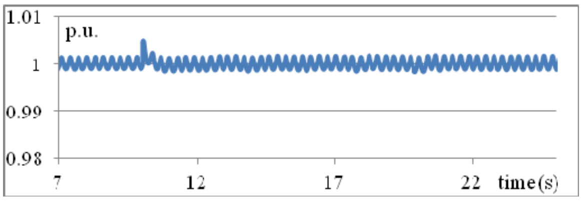


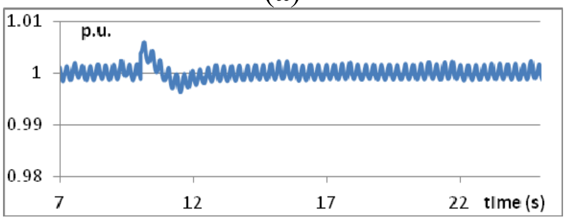
Figure 14. MVARs from STATCOM obtained using three methods: (**a**) traditional PID; (**b**) T1 fuzzy rules; (**c**) IT2 fuzzy rules (Scenario 3).

4.4. Unscheduled Photovoltaic Outage

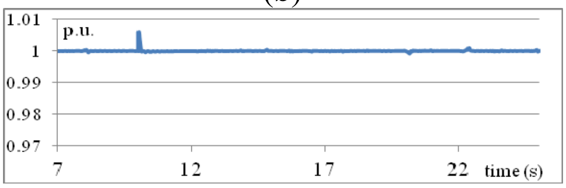
In this scenario, an unscheduled PV outage occurs at t = 10 s. Figure 15 reveals that the voltage increases rapidly at t = 10 s. The proposed method attains quickly-damped voltage variations. The dynamic voltage obtained by the T1 fuzzy rules is slowly damped from t = 10 to 12 s and oscillates as t approaches infinity. To reduce the voltage at t = 10 s, the reactive power produced from the STATCOM must be reduced as shown in Figure 16. The proposed IT2 fuzzy rule-based method outperforms both the traditional PID and T1 fuzzy rule-based methods.



(**a**)

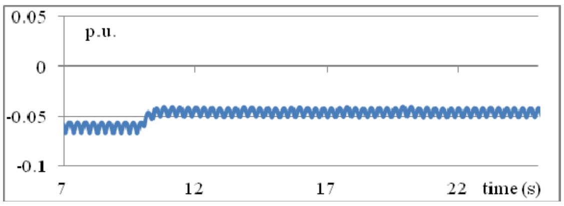


(**b**)

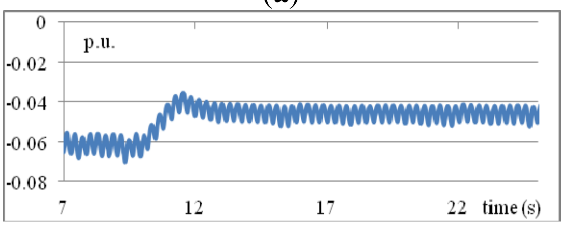


(**c**)

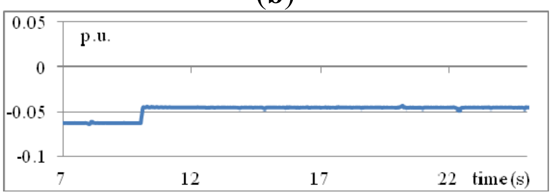
Figure 15. Voltages at bus 3 obtained using three methods: (**a**) traditional PID; (**b**) T1 fuzzy rules; (**c**) IT2 fuzzy rules (Scenario 4).



(**a**)



(**b**)



(**c**)

Figure 16. MVARs from STATCOM obtained using three methods: (**a**) traditional PID; (**b**) T1 fuzzy rules; and (**c**) IT2 fuzzy rules (Scenario 4).

5. Conclusions

An interval type-II (IT2) fuzzy rule-based STATCOM is proposed to mitigate voltage variations in this paper. The voltage error and rate of change of the voltage error are utilized to serve as inputs of the IT2 fuzzy rules; the action parts of IT2 fuzzy rules produce modified voltage errors. IT2 fuzzy rules are more applicable to nonlinear and time-varying systems than traditional T1 fuzzy rules because the upper and lower membership functions are implemented in an IT2 fuzzy set. A six-bus system is used to validate the proposed method. Four scenarios that involve large load changes and variations of MW generation from a PV farm are studied. Simulation results indicate that the proposed method always outperforms the traditional PID and T1 fuzzy rule-based methods.

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Author Contributions

Ying-Yi Hong designed the IT2 fuzzy rule base, wrote this manuscript and supervised the progress of research. Yu-Lun Hsieh developed the MATLAB code, and investigated the model of STATCOM and IT2 fuzzy theory.

Conflicts of Interest

The authors declare no conflict of interest.

Appendix

The parameters of STATCOM used in this paper are as follows: R_m = 20.3 p.u., C_m = 0.123 p.u., R_{st} = 0.00813 p.u., X_{st} = 0.0325 p.u., Kc = 30, Tc = 0.001 s, Ks = 2, Ts = 0.01 s. The bases of power and voltage are 100 MVA and 23 kV, respectively.

Table A1 provides the upper and lower MFs for the IT2 fuzzy rules used in Section 4. Definitions of [a, b, c, d] and [a', b', c', d'] are given in Figure 1 of Section 2.1.

Table A1. Upper and lower membership functions.

Linguistic Variables	Upper MF [a, b, c, d]	Lower MF [a', b', c', d']
NB	[−2, −2, −1.7, −1.5]	[−2, −2, −1.5, −1.2]
NS	[−1.5, −1.2, −1, −0.5]	[−1.2, −1.1, −1.1, −1]
ZR	[−1, −0.5, 0.5, 1]	[−0.5, 0, 0, 0.5]
PS	[0.5, 1, 1.2, 1.5]	[1, 1.1, 1.1, 1.2]
PB	[1.2, 1.5, 2, 2]	[1.5, 1.7, 2, 2]

References

1. Wang, L.; Hsiung, C.T. Dynamic stability improvement of an integrated grid-connected offshore wind farm and marine-current farm using a STATCOM. *IEEE Trans. Power Syst.* **2011**, *26*, 690–699.
2. Wang, L.; Truong, D.N. Dynamic stability improvement of four parallel-operated PMSG-based offshore wind turbine generators fed to a power system using a STATCOM. *IEEE Trans. Power Deliv.* **2013**, *28*, 111–119.
3. Beza, M.; Bongiorno, M. An adaptive power oscillation damping controller by STATCOM with energy storage. *IEEE Trans. Power Syst.* **2015**, *26*, 484–493.
4. Wang, K.Y.; Crow, M.L. Power system voltage regulation via STATCOM internal nonlinear control. *IEEE Trans. Power Syst.* **2011**, *26*, 1252–1262.
5. Chen, C.S.; Lin, C.H.; Hsieh, W.L.; Hsu, C.T.; Ku, T.T. Enhancement of PV penetration with DSTATCOM in Taipower distribution system. *IEEE Trans. Power Syst.* **2013**, *28*, 1252–1262.
6. Aziz, T.; Hossain, M.J.; Saha, T.K.; Mithulananthan, N. VAR planning with tuning of STATCOM in a DG integrated industrial system. *IEEE Trans. Power Deliv.* **2013**, *28*, 875–885.
7. Xu, Y.; Li, F.X. Adaptive PI control of STATCOM for voltage regulation. *IEEE Trans. Power Deliv.* **2014**, *29*, 1002–1011.
8. Zadeh, L.A. The concept of a linguistic variable and its application to approximate reasoning—I. *Inf. Sci.* **1975**, *8*, 199–249.
9. Liang, Q.L.; Mendel, J.M. Interval type-2 fuzzy logic systems: Theory and design. *IEEE Trans. Fuzzy Syst.* **2000**, *8*, 535–550.
10. Mendel, J.M.; John, R.I.; Liu, F.L. Interval Type-2 fuzzy logic systems made simple. *IEEE Trans. Fuzzy Syst.* **2006**, *14*, 808–821.
11. Juang, C.F.; Chen, C.Y. An interval type-2 neural fuzzy chip with on-chip incremental learning ability for time-varying data sequence prediction and system control. *IEEE Trans. Neural Netw. Learn. Syst.* **2014**, *25*, 216–228.
12. Juang, C.F.; Jang, W.S. A type-2 neural fuzzy system learned through type-1 fuzzy rules and its FPGA-based hardware implementation. *Appl. Soft Comput.* **2014**, *18*, 302–313.
13. Lin, Y.Y.; Liao, S.H.; Chang, J.Y.; Lin, C.T. Simplified interval type-2 fuzzy neural networks. *IEEE Trans. Neural Netw. Learn. Syst.* **2014**, *25*, 959–969.
14. Lin, Y.Y.; Chang, J.Y.; Lin, C.T. A TSK-type-based self-evolving compensatory interval type-2 fuzzy neural network (TSCIT2FNN) and its applications. *IEEE Trans. Ind. Electron.* **2014**, *61*, 447–459.
15. Mendel, J.M. General type-2 fuzzy logic systems made simple: A tutorial. *IEEE Trans. Fuzzy Syst.* **2014**, *22*, 1162–1182.
16. Tripathy, M.; Mishra, S. Interval type-2-based thyristor controlled series capacitor to improve power system stability. *IET Génér. Transm. Distrib.* **2011**, *5*, 209–222.
17. Khosravi, A.; Nahavandi, S.; Creighton, D.; Srinivasan, D. Interval type-2 fuzzy logic systems for load forecasting: A comparative study. *IEEE Trans. Power Syst.* **2012**, *27*, 1274–1282.
18. Mikkili, S.; Panda, A.K. Types-1 and -2 fuzzy logic controllers-based shunt active filter Id–Iq control strategy with different fuzzy membership functions for power quality improvement using RTDS hardware. *IET Génér. Transm. Distrib.* **2013**, *6*, 818–833.

19. Jafarzadeh, S.; Fadali, M.S.; Evrenosoğlu, C.Y. Solar power prediction using interval type-2 TSK modeling. *IEEE Trans. Sustain. Energy* **2013**, *4*, 333–339.
20. Khosravi, A.; Nahavandi, S. Load forecasting using interval type-2 fuzzy logic systems: Optimal type reduction, *IEEE Trans. Ind. Inf.* **2014**, *10*, 1055–1063.
21. Murthy, C.; Varma, K.A.; Roy, D.S.; Mohanta, D.K. Reliability evaluation of phasor measurement unit using type-2 fuzzy set theory. *IEEE Syst. J.* **2014**, *8*, 1302–1309.
22. Wu, D.R. On the fundamental differences between interval type-2 and type-1 fuzzy logic controllers. *IEEE Trans. Fuzzy Syst.* **2012**, *20*, 832–848.
23. Mendel, J.M. *Uncertain Rule-Based Fuzzy Logic Systems: Introduction and New Directions*; Prentice-Hall: Upper Saddle River, NJ, USA, 2001.
24. NEPLAN 5.5 User Manual. Available online: http://www.neplan.ch/ (accessed on 18 August 2015).
25. Alajmi, B.N.; Ahmed, K.H.; Finney, S.J.; Williams, B.W. Fuzzy-logic-control approach of a modified hill-climbing method for maximum power point in microgrid standalone photovoltaic system. *IEEE Trans. Power Electron.* **2011**, *26*, 1022–1030.
26. Mokhtari, M.; Aminifar, F.; Nazarpour, D.; Golshannavaz, S. Wide-area power oscillation damping with a fuzzy controller compensating the continuous communication delays. *IEEE Trans. Power Syst.* **2013**, *28*, 1997–2005.
27. Sadeghzadeh, S.M.; Ehsan, M.; Said, N.H.; Feuillet, R. Improvement of transient stability limit in power system transmission lines using fuzzy control of FACTS devices. *IEEE Trans. Power Syst.* **1998**, *13*, 917–922.
28. Chang, H.C.; Wang, M.H. Neural network-based self-organizing fuzzy controller for transient stability of multimachine power systems. *IEEE Trans. Energy Convers.* **1995**, *10*, 339–347.
29. Hilloowala, R.M.; Sharaf, A.M. A rule-based fuzzy logic controller for a PWM inverter in a stand alone wind energy conversion scheme. *IEEE Trans. Ind. Appl.* **1996**, *32*, 57–65.
30. Hosseinzadeh, N.; Kalam, A. A rule-based fuzzy power system stabilizer tuned by a neural network. *IEEE Trans. Energy Convers.* **1999**, *14*, 773–779.
31. Hoang, P.; Tomsovic, K. Design and analysis of an adaptive fuzzypower system stabilizer. *IEEE Trans. Energy Convers.* **1996**, *11*, 445–461.
32. Talla, J.; Streit, L.; Peroutka, Z.; Drabek, P. Position-based T-S fuzzy power management for tram with energy storage system. *IEEE Trans. Ind. Electron.* **2015**, *62*, 3061–3071.