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A Comparison of Type-1 and Type-2 Fuzzy Logic Controller for Full Bridge Boost Converter on DC Microgrid System

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ABSTRAK

Dengan meningkatnya kebutuhan listrik, penurunan pasokan energi fosil, serta sulitnya pendistribusian listrik ke daerah terpencil merupakan beberapa masalah yang mendesak. Energi matahari melalui panel surya dapat digunakan untuk mendukung sistem DC Microgrid serta cocok untuk jaringan listrik skala kecil. Full Bridge Boost Converter dengan transformator frekuensi tinggi yang dikendalikan oleh Fuzzy Logic Type-1 (T1FL) dan Fuzzy Logic Type-2 (T2FL) merupakan salah satu pilihan yang dapat dilakukan untuk memaksimalkan pemanfaatan energi matahari sehingga dapat meningkatkan efisiensi serta keandalan sistem pada DC Microgrid dengan menjaga tegangan keluaran menjadi konstan. Dari hasil pengujian dapat diketahui bahwa dengan menggunakan T2FL dapat menjaga tegangan keluaran Full Bridge Boost Converter dapat mencapai tegangan setpoint 320V dengan kesalahan sebesar 0.16% dan stabil dalam 0.59742ms. Sementara, T1FL memerlukan 0.7161ms untuk mencapai setpoint dengan kesalahan 2.8%.

Kata kunci*: full bridge boost converter, T2FL, T1FL, DC Microgrid*

ABSTRACT

The increasing electricity demand, the decreasing supply of fossil energy, and the difficulty in distributing electricity to remote areas are some of the urgent problems. Solar energy through solar panels can be used to support DC Microgrid systems and is suitable for small-scale power grids. Full Bridge Boost Converter with high-frequency transformers controlled by Fuzzy Logic Type-1 (T1FL) and Fuzzy Logic Type-2 (T2FL) is one of the choices that can be made to maximize the use of solar energy to increase the efficiency and reliability of systems on DC Microgrids by keeping the output voltage constant. From the test results, it can be seen that using T2FL can maintain the output voltage of the Full Bridge Boost Converter which can reach a setpoint voltage of 320V with an error of 0.16% and is stable within 0.59742ms. Meanwhile, T1FL takes 0.7161ms to reach the setpoint with an error of 2.8%.

Keywords*: full bridge boost converter, T2FL, T1FL, DC Microgrid*

1. INTRODUCTION

The industrialization and advancement of the current age are driving an increasing demand for energy to support a growing global population **(Paul et al., 2021)**. In 2050, there will likely be 9 billion more people living on the planet **(Halkos & Gkampoura, 2020)(Masnadi et al., 2015)**. It is anticipated that as a result, the global energy demand will rise by almost 50% **(Halkos & Gkampoura, 2020).** The growing reliance on fossil fuels to supply the world's energy demands is a result of the growing population. However, there are fewer fossil fuels available, and their cost is going up. The production of power using fossil fuels suffers as a result of this. Therefore, renewable energy is currently being used as a substitute energy, and it is anticipated that this will modify the current distribution pattern and lead to a more ecologically friendly power producing system **(Prastyawan et al., 2021)**. Solar energy is among the numerous forms of renewable energy that have been created. Solar panels can transform solar energy into a kind of electrical energy that humans can use more effectively and which is needed **(Abdulrazzaq & Ali, 2018)**. Using solar panels offers several advantages as they are low-maintenance, eliminate the need for fossil fuel-dependent systems that demand regular upkeep, and are environmentally friendly by minimizing pollution.

The variability of weather conditions poses a challenge to the optimal absorption of sunlight by solar panels, leading to incomplete utilization of available sunlight. Consequationuently, optimizing the energy generation from solar panels becomes a complex task due to this unpredictability **(Majdi et al., 2021)**. Solar panels encounter fluctuations in voltage and current due to changes in temperature and irradiation levels. These variations in environmental conditions lead to varying electrical characteristics in the output of the solar panels **(Arsandi et al., 2022)**. The DC Microgrid technology harnesses the power of solar energy, which is a sustainable and renewable source of electricity **(Ahmad et al., 2021)**. A small-scale grid system called a DC Microgrid can function on its own or in conjunction with the main electrical grid which can reach remote areas because it can utilize renewable energy as a power **(El-Shahat & Sumaiya, 2019)**. Using a power converter output-maximizing algorithm will ensure that solar panels provide the DC Microgrid system with the highest level of energy efficiency feasible. T1FL **(Unde et al., 2020)** and T2FL **(Tiwary et al., 2021)** are two algorithms that have the potential to enhance the output power of power converters utilizing solar panel sources. It is ideal for use in fuzzy logic control under resilience, dynamics, and uncertainty situations that range from straightforward to quite complex, one of which is for solar panel-powered systems **(Prastyawan et al., 2021)**. Different levels of flexibility distinguish T1FL from T2FL controls **(Carreon-Ortiz et al., 2022)(Prastyawan et al., 2021)(Shukla & Tripathi, 2014)**.

The power converter utilized in the DC Microgrid employs a specific topology known as the Full Bridge Boost Converter, specially engineered to accommodate solar panel installations. The Full Bridge Boost Converter **(Górecki et al., 2022)** is a distinct DC to DC Converter topology designed specifically to amplify voltage and deliver a consistent output voltage **(Ríos et al., 2021)**. A converter with this topology can produce a DC voltage output with a range greater than the DC input voltage depending on the type of step-up or step-down high-frequency transformer **(Lim et al., 2019)(Rahrovi et al., 2021)**. In this system, a full bridge rectifier is utilized to convert the AC waveform on the secondary side of the isolated high-frequency transformer into a DC waveform **(Ibrahim et al., 2017)(Prastyawan et al., 2021)**. At the same time, the primary side of the transformer receives a square AC waveform **(Xu et al., 2021)** produced by high-frequency switching. Using this system, the voltage value in the converter circuit is modified in two steps. To minimize voltage losses before connecting to the load, the Full Bridge Boost Converter circuit also includes an LC filter with a high-frequency inductor **(Selman, 2016)**, this filter is included to attenuate high-frequency components and ensure a smoother output voltage. The research in this work is to build a Full Bridge Boost Converter architecture as a power conversion tool by comparing the T1FL and T2FL approaches to ensure the best converter output voltage so that it is able to produce and distribute electricity both on a small scale and reach remote areas according to various references that have been researched.

2. RESEARCH METHODS

2.1 System design

The system design for this Full Bridge Boost Converter is shown in Figure 1.

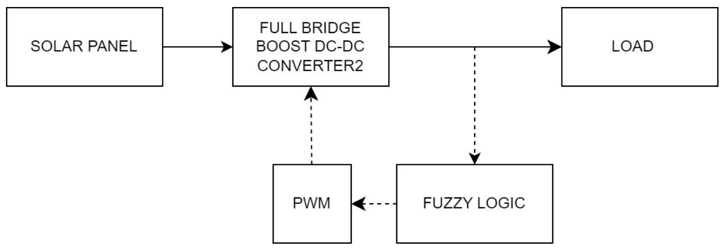


Figure 1. Block Diagram System

Solar panels are employed as the primary energy source for a Full Bridge Boost Converter. This is used to regulate and maintain a stable voltage output from the solar panels. This regulated output voltage can then be used to power various loads, including inverter loads and other DC devices. To ensure a stable and desired output voltage, a controller is employed to regulate the Full Bridge Boost Converter. This regulation process utilizes two techniques known as T1FL and T2FL. These Fuzzy techniques enable precise and effective voltage regulation, allowing the output voltage to consistently reach a predetermined setpoint.

2.2 System modeling

2.2.1 Full bridge boost converter

The Full Bridge Boost Converter is a type of DC converter that operates with electrical isolation and is designed to increase voltage at a high-frequency. This design offers significant advantages for applications requationuiring high power **(Alavi & Dolatabadi, 2015)**, as it uses a magnetic core and switching components to ensure increased efficiency at power levels of up to thousands of watts. The circuit topology of the Full Bridge Boost Converter involves several key components. These include a high-frequency transformer that provides power to a full bridge rectifier, an LC filter that incorporates a high-frequency inductor to condition the output before it reaches the load, and a half bridge switching circuit. The circuit topology of the Full Bridge Boost Converter is depicted in the diagram Figure 2.

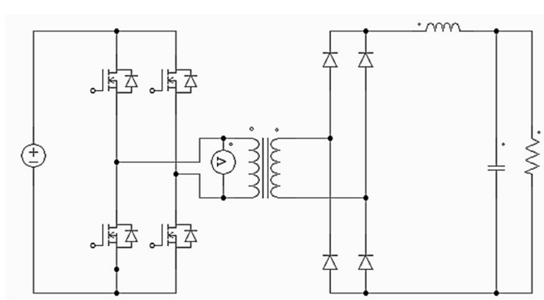


Figure 2. The Full Bridge Boost Converter's Circuit Topology

The Full Bridge Boost Converter transfers current from its input to its output by utilizing four high-frequency semiconductor switches. These switches cycle through four distinct operational states or process conditions during the conversion process. During the operation of the Full Bridge Boost Converter, specifically during condition 1, certain characteristics or behaviors can be observed, Q1 and Q4 switch. When Q2 and Q3 are OFF, current will move through Q1 and Q4, respectively, as a result of the two switches being ON. In condition 1 operation of the Full Bridge Boost Converter, a positive voltage is applied to the primary winding side of the transformer's secondary side. Before reaching the output of the converter, the filter circuit receives current from diodes D1 and D3. When condition 1 is met within the time interval $0 < t < dT$, both Q1 and Q4 are simultaneously turned on, resulting in a secondary-side voltage that aligns with the equation specified as Equation (1).

$$V_{sec} = \frac{N_s}{N_p} V_{in} \tag{1}$$

The Equation (2) provides the value of the inductor output voltage (V_L).

$$V_L = \frac{N_s}{N_p} V_{in} - V_{out} \tag{2}$$

Based on the following Equation (3), The inductor output current (i_L) will increase steadily in a linear manner.

$$I_L(0) = i_{Lout(pk)} - V_o(0.5 - D)\frac{T}{L_{out}} \tag{3}$$

During switching condition 2, all switches in the Full Bridge Boost Converter are turned OFF. During the end of condition 1 in Figure 3, while the diodes D1 and D2 are forward biased and magnetize the current generated at the end of condition 1.

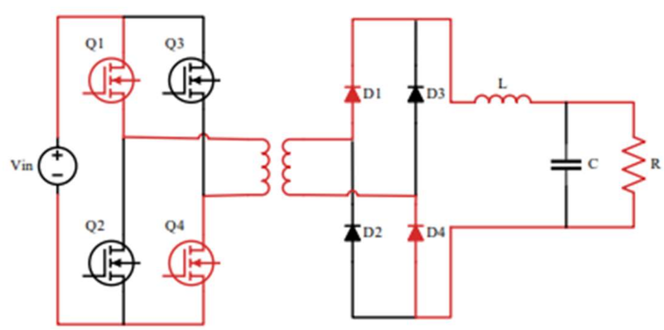


Figure 3. The Current Flow Pattern of Full Bridge Boost Converter Condition 1

During switching condition 3 in Figure 5, switches Q1 and Q4 are in the ON state, while Q2 and Q3 are in the OFF state. Upon receiving the reverse voltage on the primary side of the transformer, a negative flow direction is observed on the secondary side. During this switching condition, current is allowed to flow in both directions, to the LC filter circuit and the output side of the converter. This is achieved through the utilization of diodes D2 and D3. Similar to switching condition 2 in Figure 4.

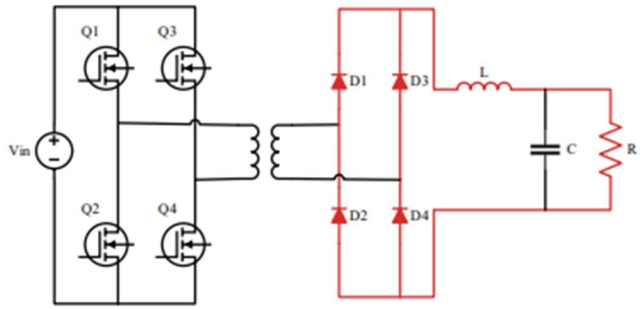


Figure 4. The Current Flow Pattern of Full Bridge Boost Converter Condition 2

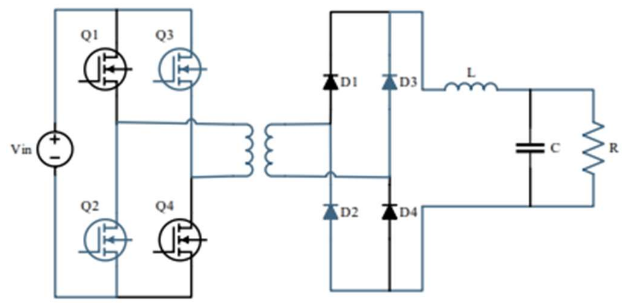


Figure 5. The Current Flow Pattern of Full Bridge Boost Converter Condition 3

When switching condition 4 occurs, all switches are OFF. As a result, the transformer's current flows via the four diodes. The value of the output voltage (V_o) of the Full Bridge Boost Converter is determined by calculating the integral of the inductor voltage (V_L) over the duration of the switching period T. The specific equations Equation (7) to Equation (9) provide the results of this calculation.

$$V_o = 2\frac{N_s}{N_p}V_s D \tag{7}$$

$$V_o = 2 \times V_s \times \frac{N_2}{N_1} \times D \tag{8}$$

$$I_{out(rms)t} = \sqrt{(I_{out})^2 + \left(\frac{\Delta I_L/2}{\sqrt{3}}\right)^2} \tag{9}$$

For number of high-frequency transformer turns is shown in the following Equation (10) to Equation (12).

$$\frac{N_2}{N_1} = \frac{V_o}{2 \times V_s \times D} \tag{10}$$

$$N_1 = \frac{D \times T \times V_s}{2 \times B_{max} \times A_c} x\ 10^4 \tag{11}$$

$$N_2 = n \times N_1 \tag{12}$$

By incorporating capacitors and inductors in the Full Bridge Boost Converter, it is feasible to reduce the magnitude of the output ripple. These components help to smooth out the variations in the output voltage, resulting in a more stable and regulated output. The Equation (13) to Equation (14), show how capacitors and inductors also help reduce component overheating brought on by heavy usage.

$$L = \frac{1}{\Delta I_L} \times \left[V_o \times \left(\frac{1}{2} - D\right) \times T\right] \tag{13}$$

$$C = \frac{(1 - D)}{8 \times L\, x\, (2f)^2 \times r_{Vo}} \tag{14}$$

The designed Full Bridge Boost Converter is specifically tailored for a load with a power capacity of 128 Watts. Its main function is to amplify the input voltage from the solar panel and convert it into a significantly higher output voltage. Table 1 below shows the design parameters of the Full Bridge Boost Converter.

Table 1. Specification And Characteristics of The Full Bridge Boost Converter

Parameters	**Value**	**Units**
V_s	34.6	Volt
V_o	320	Volt
D_{max}	45	Percent
Efficiency	80	Percent
P_{in}	160	Watt
Frequency	100	kHz
P_{out}	128	Watt
Current Ripple	0.125	Ampere
Voltage Ripple	0.32	Volt

2.2.2 T1FL methods

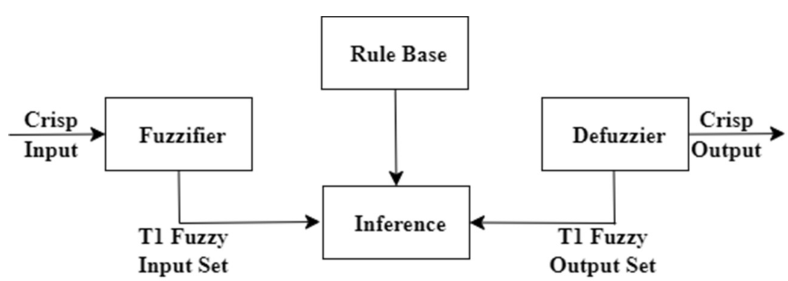


Figure 6. T1FL System

The T1FL system is shown in Figure 6 T1FL is widely utilized as it is the most commonly employed form of Fuzzy Logic. However, it has a limitation in dealing with a restricted level of uncertainty. In practical system implementations, high levels of uncertainty are often encountered due to the varying complexity levels of the systems involved **(Meylani & Handayani, 2017)**. T1FL system comprises three primary processes: fuzzification, inference, and defuzzification. The degree of membership in T1FL has an interval value between 0 to 1. This T1FL uses a 7x7 membership function with a rule base as shown in Table 2.

A. Fuzzifier
   Fuzzifier is a process of mapping input values into Fuzzy sets using membership functions.
B. Inference
   Inference is a decision-making mechanism based on the principles of Fuzzy Logic.
C. Defuzzification
   Defuzzification refers to the process of transforming a set of fuzzy logic conclusions into a crisp or numerical output value in T1FL.

Table 2. The Rule Base of T1FL System

	NB	**NM**	**NS**	**Z**	**PS**	**PM**	**PB**
NB	NB	NB	NB	NM	NM	NS	Z
NM	NB	NB	NM	NM	NS	Z	PS
NS	NB	NM	NS	NS	Z	PS	PM
Z	NB	NM	NS	Z	PS	PM	PB
PS	NM	NS	Z	PS	PM	PM	PB
PM	NS	Z	PS	PM	PM	PB	PB
PB	Z	PS	PS	PB	PB	PB	PB

In the internal system, use T1FL with a 7x7 display function to display input and output values according to system planning. The membership function utilized in the internal system takes the form of a triangular shape, as illustrated in. Figure 7 to Figure 8.

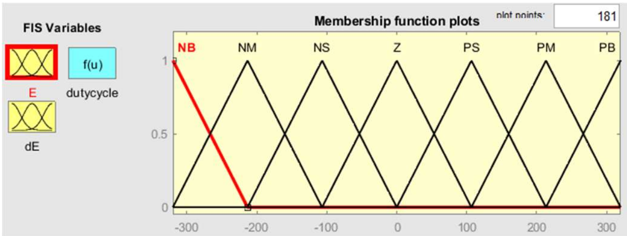


Figure 7. Membership Function Error

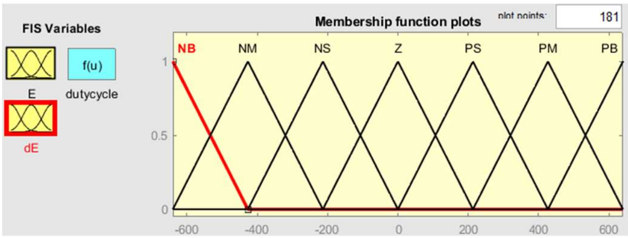


Figure 8. Membership Function Delta Error

Fuzzy output determination can be seen in Figure 9.

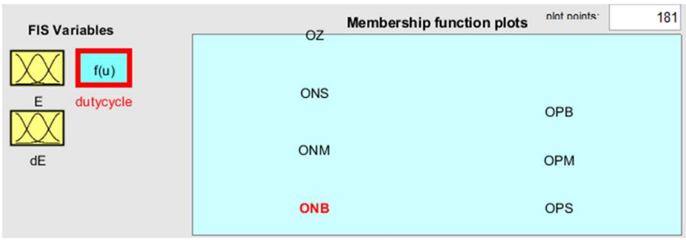


Figure 9. Output T1FL

2.2.3 T2FL methods

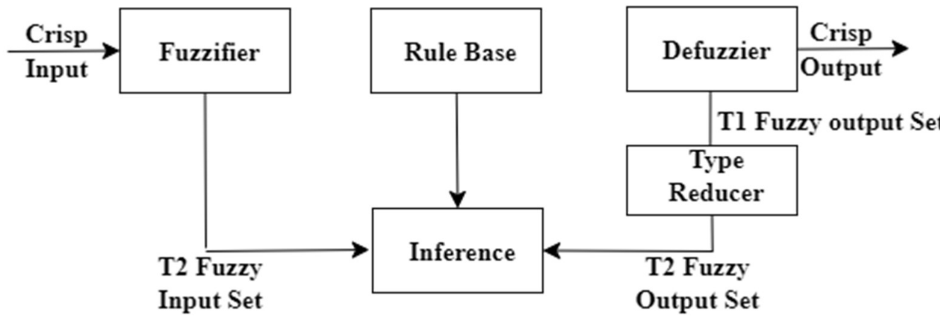
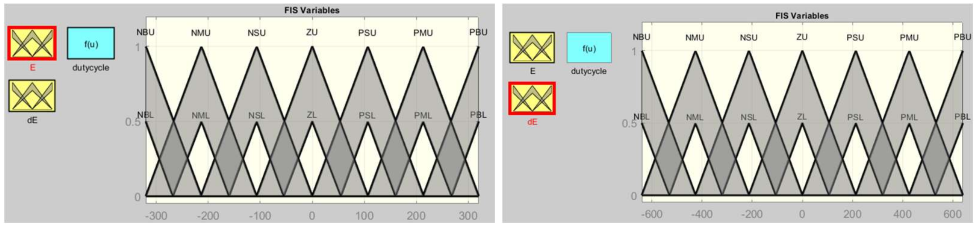


Figure 10. T2FL System

The T2FL system is shown in Figure 10 Fuzzification in T2FL systems refers to the process of converting specific quantities or variables into membership values within the set. This conversion allows for the representation of uncertainty and variability in a more comprehensive manner. In a T2FL system, the process of establishing the boundaries or limits of the Lower Membership Function or commonly abbreviated as LMF and Upper Membership Function or commonly abbreviated as UMF is crucial. This step defines the range of uncertainty or variability in the membership values assigned to different elements within the system. UMF and LMF in a T2FL system are positioned at the highest and lowest Footprint of Uncertainties or so called FOU values represent the upper and lower bounds of the uncertainty range in the system. The FOU represents the range or extent of uncertainty or variability in the membership values assigned to elements within the system. The uncertainty surrounding the degree of primary membership in a T2FL membership function is encapsulated within a limited region called FOU. This FOU represents the range or area where the degree of uncertainty exists within the membership function. UMF and LMF are two membership function of Type-1 limiting membership functions that confine the interval membership function of the FOU in T2FL. These membership functions define the upper and lower limits of the uncertainty range within the FOU. Upper is the set the part that has the highest degree of membership in the FOU. While lower is the degree of membership which is part of the degree of primary membership.

The inference is an integral component of the Fuzzy Logic concept, serving as a framework for decision-making. The degrees of membership are blended in accordance with pre-established rules after the previous phase. In T2FL, the conclusion set is expanded to incorporate the cut and input active rules. The type-reducer process is a unique process specific to T2FL and is not present in the main logic system of T1FL. Reduction is the process of transforming a T2FL output set into a T1FL set by narrowing down the uncertainty and obtaining a more precise output representation. The output is then given the outcomes of the defuzzification of this reduction set.

In T1FL, defuzzification can be described as a process that converts the fuzzy output values from a set of conclusions into crisp or definite values, which are then utilized as the output of T1FL. Besides that, after the reduction stage or type reducer, the output of the reduction set in T2FL remains in the form of T2FL. The T2FL system's working space is divided into two sections: positive and negative. Based on the input and output parameters of the T2FL algorithm, as per the specified input and output variables.Figure 11 to Figure 12 shows the membership function and the determination of the T2FL output range.



(a) (b)

Figure 11. (a) Error Membership Function, (b) Delta Error Membership Function

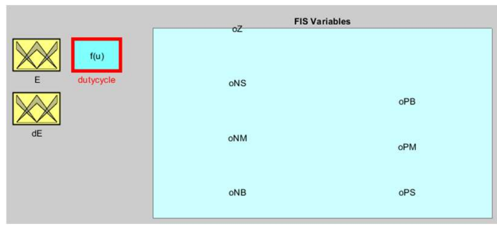


Figure 12. Output of T2FL

3. RESULTS AND DISCUSSION

To determine the value of the output voltage of the Full Bridge Boost Converter, a simulation can be performed using Simulink in MATLAB. Figure 14 illustrates the circuit of the Full Bridge Boost Converter operating with a solar panel source, without the implementation of a control method, while Figure 15 shows a series of the entire system using the T2FL method.

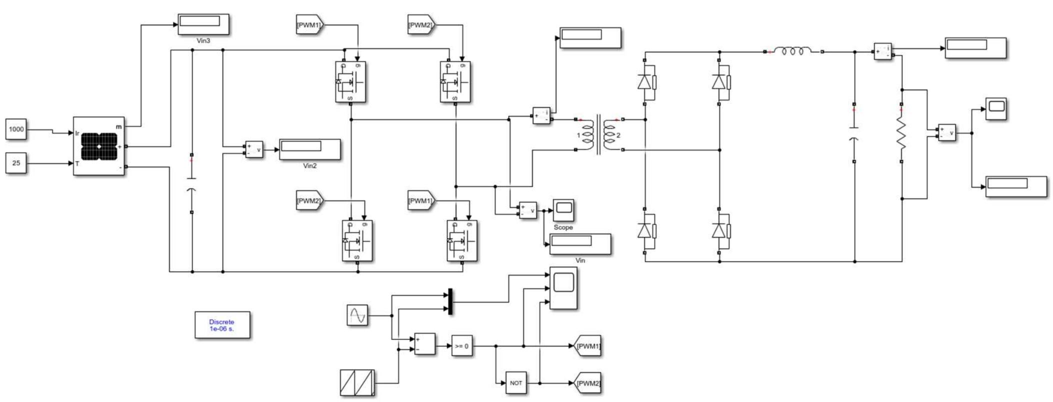


Figure 14. The Circuit of Full Bridge Boost Converter without Control Method

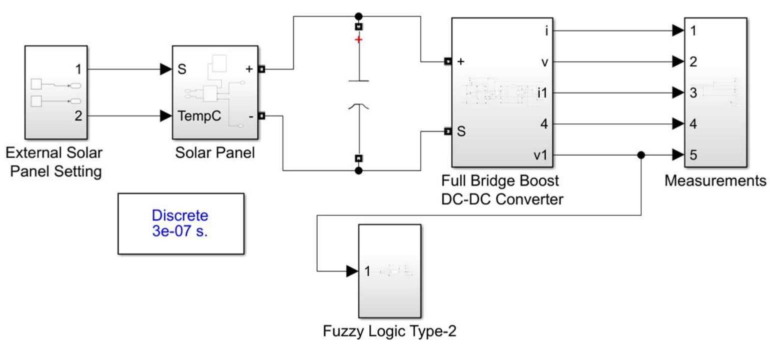


Figure 15. Modelling The Overall System

While the MATLAB Simulink network for the T2FL algorithm used is found in Figure 16.

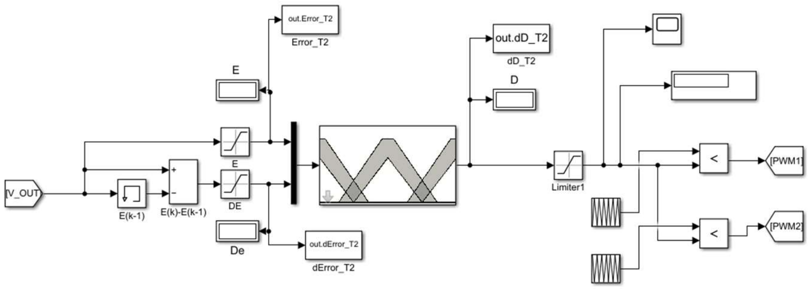


Figure 16. T2FL Block Diagram Model

The results of the Full Bridge Boost Converter circuit simulation without control can be seen in Figure 17.

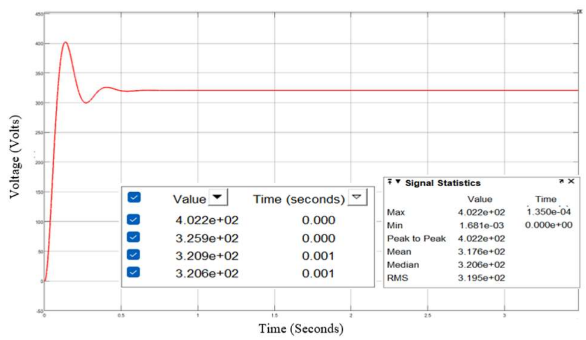


Figure 17. The Output Voltage Waveform Without Algorithm

Figure 17 demonstrates that in the simulation of a Full Bridge Boost Converter without employing a control algorithm to regulate the output voltage, significant voltage ripples are observed. These ripples result in a longer time for the waveform to reach a stable state or, in other words, for the voltage to reach the desired set point voltage of 320 Volts. However, in a DC Microgrid system, optimal performance cannot be achieved if certain components fail to reach the desired set point voltage condition. So, to reach the set point voltage condition, the T2FL method is used because it is considered to have a system circuit structure as shown in Figure 15.

This converter system is simulated using Simulink MATLAB with solar panel irradiation of 1000W/m^2 with a temperature of 25℃ and a solar panel output voltage of 34.6 Volts. To achieve the set point voltage condition, has two input parameters for T2FL, namely Error and Delta Error (dE), with the following Equation (15) to Equation (16).

$$E = V_k - V_{set} \quad (15)$$

$$dE = E_k - (E_k - 1) \quad (16)$$

$E = Error$
$dE = Delta\ Error$
$V_k = Actual\ Voltage$
$V_{set} = Setpoint\ Voltage$
$E_k = Current\ Error$
$E_k - 1 = Previous\ Error$

Figure 18 depicts a flowchart of a T2FL system, which includes two input parameters. The system utilizes a 7x7 membership function to overcome the uncertainty associated with these two input parameters.

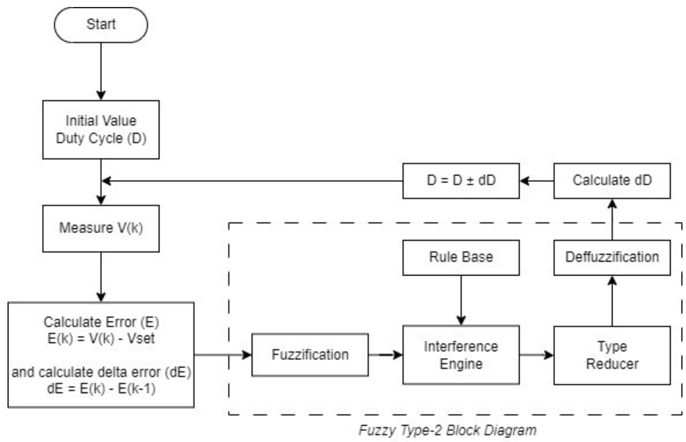


Figure 18. T2FL System Flowchart

Upon simulation using T2FL, the Full Bridge Boost Converter generates an output voltage of 320.1 Volts. This value of the output voltage is remarkably close to the set point voltage, indicating a high level of precision. The waveform of the output voltage is illustrated in Figure 19.

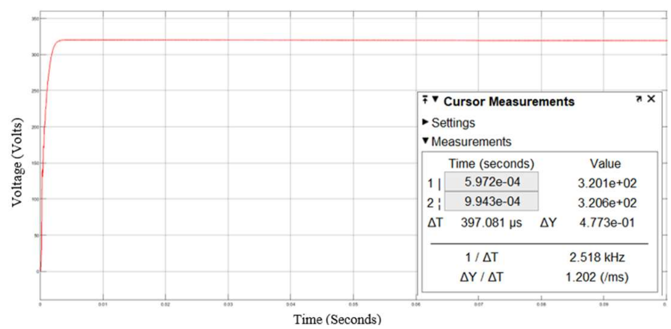


Figure 19. The Output Voltage Waveform Uses The T2FL

The simulation results of the Full Bridge Boost Converter circuit demonstrate a steady and constant output voltage waveform without any visible ripples. The voltage quickly reaches a stable state without any fluctuations or disturbances. By using the T2FL algorithm, the resulting output voltage is 320.1 Volts and reaches a steady state at $5.972 \times 10^{-4} S$. The speed of the T2FL algorithm in reaching the set point condition is 320 Volts because this algorithm uses a 7x7 membership function where the greater the membership function used, the better the results can be. To compare the results of the converter output voltage, the T2FL algorithm is compared with T1FL. The converter simulation output waveform using the T1FL algorithm presented in Figure 20.

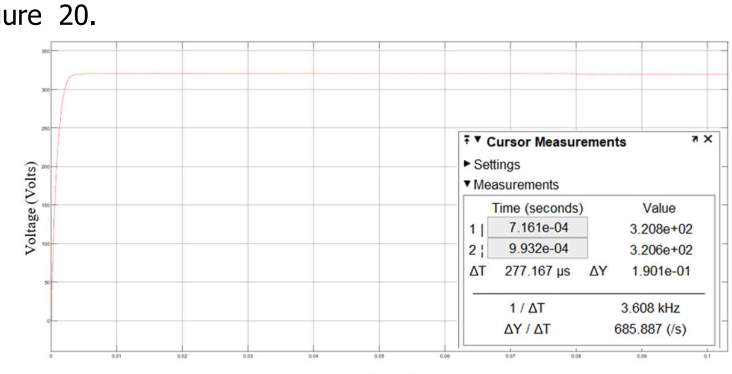


Figure 20. The Output Voltage Waveform Uses The T1FL

The results of the simulation using the T1FL algorithm in Figure 18 show that the time needed to reach a steady state is $7.161 \times 10^{-4} S$ with the voltage read when it just reaches a steady state of 320.8 Volts. So that, with the difference in the output voltage value of the resulting converter and the difference in the speed of time to reach a steady state, the two simulations with different Fuzzy logic algorithms are compared. T2FL is a perfection of T1FL. The simulation results using these two algorithms presented in Table 3 to Table 4.

Table 3. Simulation Results Using T2FL

T2FL										
Irradiance (W/m^2)	**Temp (°C)**	**Vin (V)**	**Vout Simulation (V)**	**Vout Design (V)**	**Iin (A)**	**Iout (A)**	**Pin (W)**	**Pout (W)**	**Eff (%)**	**Error Vout (%)**
1000	25	34.60	320.80	319.80	5.72	0.59	198.05	188.31	95.08%	0.31%
950	25	34.54	320.20	319.25	5.25	0.51	181.37	163.94	90.39%	0.30%
900	25	34.18	321.46	322.94	5.17	0.49	176.71	157.19	88.96%	0.46%
850	25	33.91	319.87	320.39	4.38	0.41	148.53	131.15	88.30%	0.16%
800	25	33.82	320.33	319.54	4.35	0.37	147.12	118.84	80.78%	0.25%
750	25	33.83	320.51	319.63	4.21	0.36	142.42	116.02	81.46%	0.27%

Table 4. Simulation Results Using T1FL

T1FL										
Irradiance (W/m^2)	**Temp (°C)**	**Vin (V)**	**Vout Simulation (V)**	**Vout Design (V)**	**Iin (A)**	**Iout (A)**	**Pin (W)**	**Pout (W)**	**Eff (%)**	**Error Vout (%)**
1000	25	34.60	321.23	319.81	5.71	0.58	197.70	187.28	94.73%	0.44%
950	25	34.54	324.70	319.25	5.24	0.51	181.06	164.30	90.74%	1.71%
900	25	34.18	325.98	322.95	5.16	0.45	176.47	145.06	82.20%	0.94%
850	25	33.91	329.43	320.40	4.38	0.31	148.53	101.79	68.54%	2.82%
800	25	33.82	330.12	326.49	4.35	0.31	147.12	103.00	70.01%	1.11%
750	25	33.83	330.45	326.59	4.21	0.30	142.42	98.80	69.37%	1.18%

Table 3 to Table 4 presents the simulation results of the Full Bridge Boost Converter, comparing the results obtained using two different algorithms. The simulation also includes disturbances in the form of varying irradiation on solar panels, assuming they are influenced by weather conditions so that changes in solar panel irradiation and voltage occur. By introducing different irradiation variables, the simulation aims to demonstrate the effectiveness of the same Fuzzy Logic algorithm using the 7x7 membership function in achieving the desired set point voltage for the converter.

In Table 3 it can be seen that solar panels experience interference in the form of varying irradiation which is adjusted to the actual conditions of solar panels whose irradiation can change because the position and conditions of the sun can change every hour. In particular the performance of solar panels is evaluated at maximum irradiation conditions. Table 3 describes the condition of the system controlled using T2FL so that it can reach a set point voltage of 320 Volts with stable conditions even though the solar panel irradiation varies with an output voltage error of 0.18%. So that if the output voltage of this converter is used to supply household needs it will not cause damage to electronic devices or components used when distributing electricity.

Whereas in Table 4 which is the result of a simulation using the T1FL control which also experiences interference in the form of varying irradiation, it can be seen that the output voltage generated by the converter is not yet stable enough to reach the set point output voltage. The resulting voltage exceeds the design output voltage with an error of 2.8%. The error is much larger than when using the T2FL control. If the generated voltage is not in accordance with the design that has been made later, it can cause damage to the system components.

The difference in the capabilities of the 2 Fuzzy logic algorithms is that T2FL can resolve more complex uncertainties so that the output voltage value of the Full Bridge Boost Converter simulation when using T2FL is more constant and there are no ripples in the waves.

4.CONCLUSION

Based on the simulation results, the Full Bridge Boost Converter circuit with the addition of the Type-1 Fuzzy control method reaches a steady state set point at $7.161 \times 10^{-4} S$. However, it exhibits an error value of 2.82% and still has ripples in the output voltage waveform. Besides that, when employing the T2FL control method, the circuit achieves the set point with steady conditions at $5.972 \times 10^{-4} S$. It demonstrates a lower error value of 0.16% and produces a completely ripple-free output voltage waveform during the steady state. Thus, the use of the T2FL control method proved to be superior to T1FL in optimizing solar energy converted by the Full Bridge Boost DC-DC Converter. So that it can increase the efficiency and reliability of renewable energy in the electric power system and is ready to be used to supply electricity in remote areas.

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