Fuzzy Logic Controller for Second Order DC-DC Converters: A Comprehensive Analysis

Introduction

DC-DC converters are helpful in a variety of applications, including DC motor drives, power systems, and power supply reliability (UPS). Renewable energy sources, such as solar and wind, are now widely used to fulfil global energy demand while also producing clean energy. Variations in produced power are caused by the intermittent nature of solar and wind generation, while voltage changes are caused by load variation. As a result, DC-DC converters are required as the renewable energy output step to offer a stable and desirable output. Buck, boost, and buck-boost converters are the most often used converters. Because they are nonlinear systems of the second order, designing a controller necessitates mathematical modelling. By linearizing the plant around an operating or equilibrium point, these controls are simple to design and execute. Because of the existence of parasitic components and fluctuating loads, a controller developed using traditional approaches can only manage tiny perturbations from the equilibrium point of state and input variables. In these controllers, high signal stability comes at the cost of reduced performance.

Controlling such nonlinear systems with fuzzy logic control (FLC) is a fundamentally new method. It's been used in a variety of applications with great success. Understanding system behavior and expressing control rules in human language are required for FLC. Where linear control approaches fail, FLC expands the control capabilities to massive signal dynamics. It outperforms traditional linear controllers in terms of performance. With developments in digital technology, power converters may also be controlled by FLC.

Application of FLC in DC-DC Converters

A. DC-DC Converters

Buck, boost, and buck-boost converters are all taken into account in this FLC analysis. Figure-1 shows circuit diagrams. The output voltage of a buck converter is reduced to a level lower than the input voltage. The output voltage of a boost converter is greater than the input voltage. Buck-Boost converters change the output voltage to a greater or smaller level than the input voltage, depending on the specific application.

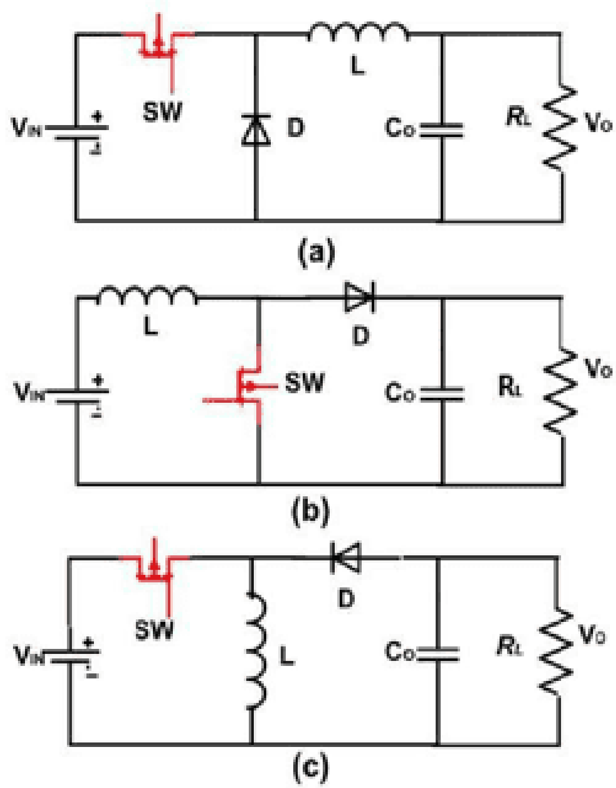


Figure-1: DC-to-DC converters (a) Boost (b) Buck (c) Buck-Boost

B. Structure of a Fuzzy Logic Controller

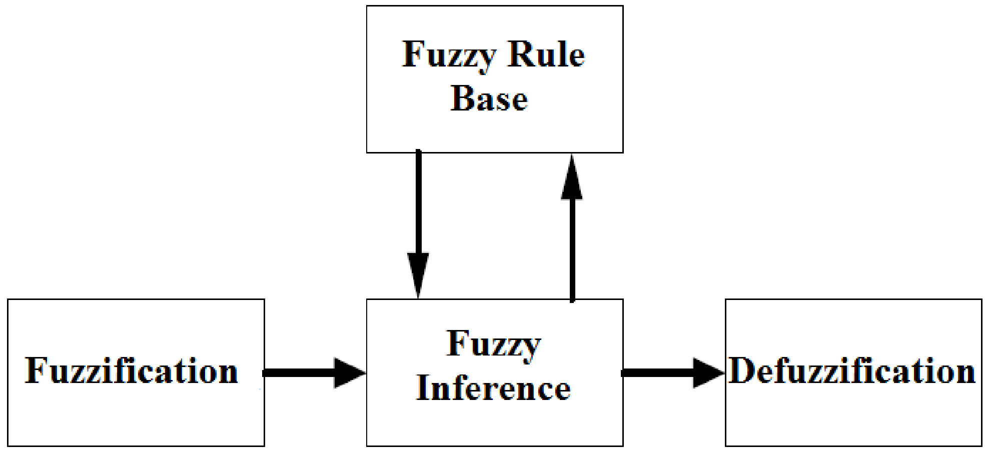


Figure-2: Fundamental Structure of Fuzzy Logic Controller

The FLC in this instance comprises two-inputs and single output. The voltage error e(n) and the rate of change in voltage error Δe(n) at nth instant, as computed by equations (1) and (2) are the inputs.

$$e(n) = Vo - Vref \quad \rightarrow (1)$$

$$\Delta e(n) = e(n) - e(n-1) \quad \rightarrow (2)$$

Where, Vo, Vref and e(n-1) denote output voltage, reference voltage and voltage error, correspondingly at the (n − 1)th instant.

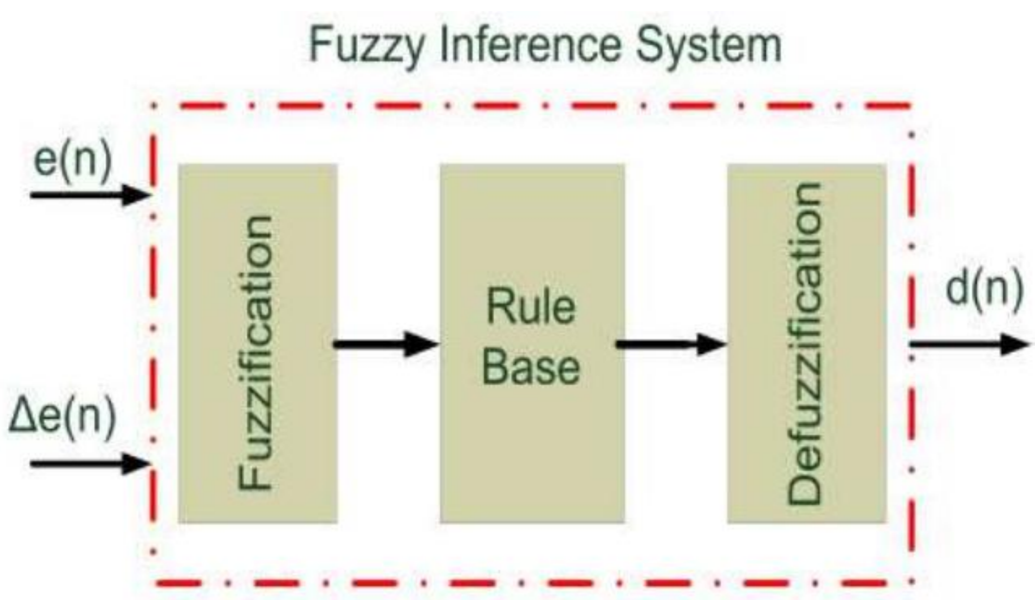


Figure-3: Structure of a Fuzzy Logic Controller

The fuzzy controller's output is the duty cycle, which is the converter's input, as stated by equation-3

$$dn = dn-1 + \eta \times \Delta d \quad \rightarrow (3)$$

Where d(n) and d(n−1) are duty cycles at nth and (n − 1)th instants correspondingly. η and Δd represent the gain and duty cycle change at each moment, respectively.

The FLC structure is comprised of three phases, as shown in Figure-3:

1) A fuzzification block that translates numeric error e(n) values and rate of change in error Δe(n) to linguistic values.
2) A rule base foundation block that provides the fuzzy rules for establishing the link between inputs and outputs.
3) A defuzzification block that transforms linguistic output into a "crisp" numerical number. The error is provided through the feedback network, as depicted in the overall system design in Figure- 4.
4) Gains Λe , Λce and η are fine-tuned to get the required output. 'Parameter Calculation & Designing' explains how to tune these parameters and how to use FLC.

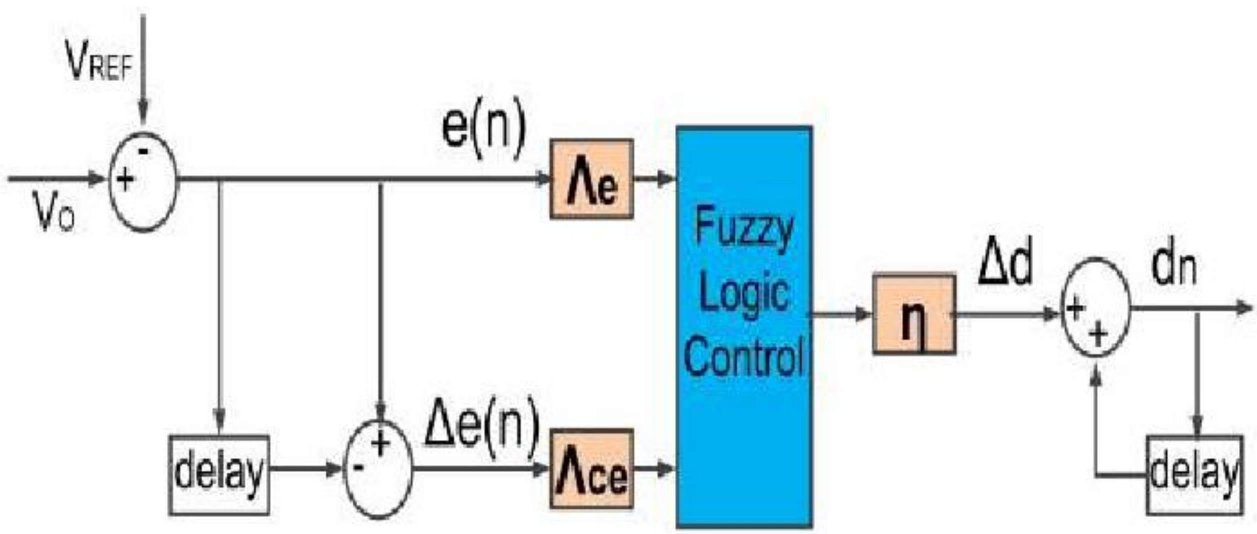


Figure-4: FLC for DC-to-DC converters

Designing and Calculating Parameters

A. Converter Designing

In continuous conduction mode, converter parameters (inductor and capacitor) are computed for the intended operation. Load requirements (e.g., operating voltage Vo, load changes), supply voltage fluctuation, and switching frequency all play a significant part in design.

For example, if we require a buck converter to step down a DC voltage from 20 volts to 15 volts while allowing for 10% current ripples, we may use the method in equation (4) to compute L and C.

The usual equations are used to determine the parameters.

TABLE I: Parameters of the Converter Circuit

Parameters	Buck	Boost	Buck-Boost
Inductance(L)	2mH	6mH	8mH
Capacitance(Co)	20µF	400µF	500µF
Load (RL)	10Ω	10Ω	10Ω
Vin (max)	20V	25V	30V
Vin (min)	15V	20V	20V
Reference Output	12V	30V	30V
Switching Frequency	5000Hz	5000Hz	5000Hz

applied in the design of DC-DC converters The computed inductor and capacitor values are the minimal values necessary to run the converter in Continuous conduction mode. To decrease ripples, values might be bigger than estimated values. Minimum inductor and capacitance calculation formulae are as follows:

- Buck Converter:

$$L = \frac{V_o \times (V_{in} - V_o)}{\Delta I_L \times f_s \times V_{in}} \tag{4}$$

$$C = \frac{\Delta I_L}{8 \times f_s \times V_{out}} \tag{5}$$

- Boost Converter:

$$L = \frac{V_{in} \times (V_o - V_{in})}{\Delta I_L \times f_s \times V_{out}} \tag{6}$$

$$C = \frac{I_{outmax} \times D}{f_s \times V_{out}} \tag{7}$$

- Buck-Boost Converter:

$$L = \frac{V_{IN} \times D}{\Delta I_L \times f_s} \tag{8}$$

$$C = \frac{I_{outmax} \times D}{f_s \times \Delta V_c} \tag{9}$$

Where Vo, Vin, ΔIL, fs, D and I(outmax) denote the output voltage, input voltage, inductor ripple current, switching frequency and maximum output current required in the application respectively.

B. Designing Fuzzy Logic Controllers

The design of a Fuzzy logic controller for a system necessitates a thorough grasp of the system's behaviour in human language. The output voltage of a converter has a mathematical relationship with the input voltage and duty cycle, as shown in equations (4), (5), and (6) for buck, boost, and buck-boost converters, respectively.

$$D = \frac{V_o}{V_{IN}} \tag{10}$$

$$D = 1 - \frac{V_{IN}}{V_o} \tag{11}$$

$$D = \frac{-V_o}{-V_o + V_{IN}} \tag{12}$$

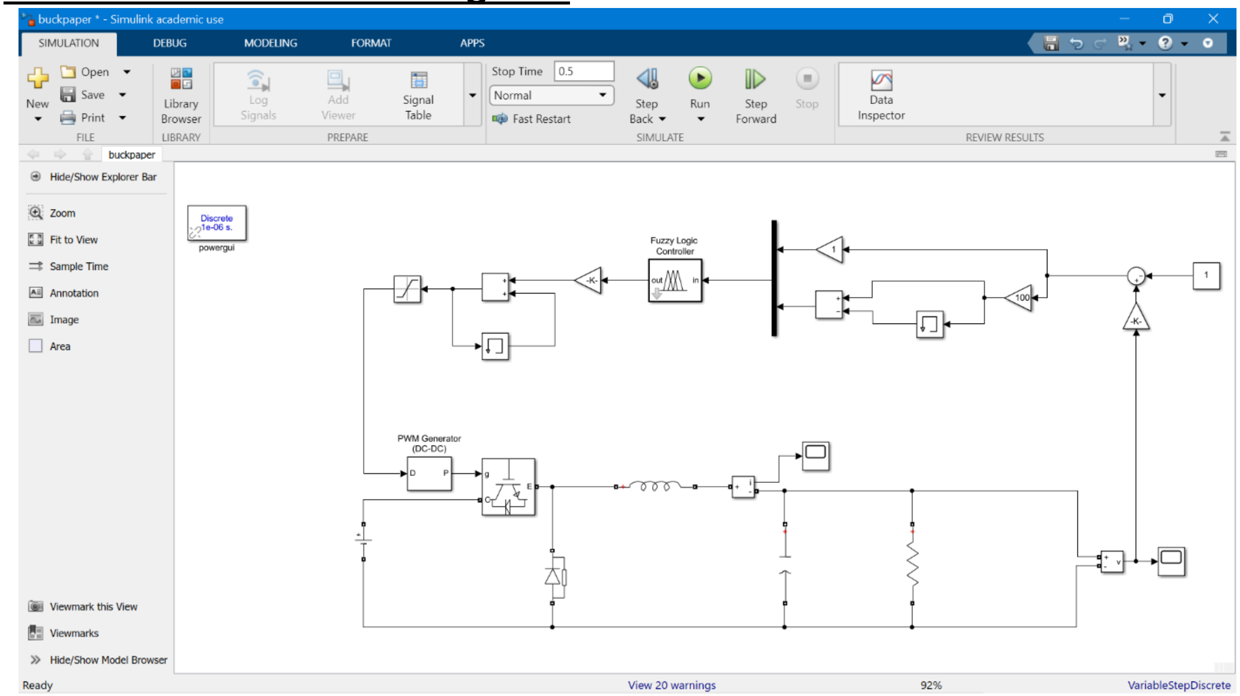
By studying these equations, we can derive a general strategy for all II order converters: "In order to raise the magnitude of any of the Second order converter's output voltage, the duty cycle must be increased." This conclusion will serve as the foundation for developing the fuzzy controller's rule base, which will be the same for all Second order converters:

- If the ERROR in output voltage would be a BIG POSITIVE number and the CHANGE IN ERROR is indeed a BIG POSITIVE quantity, therefore the DUTY CYCLE must be lowered by a large value, resulting in a BIG NEGATIVE variation in duty cycle.

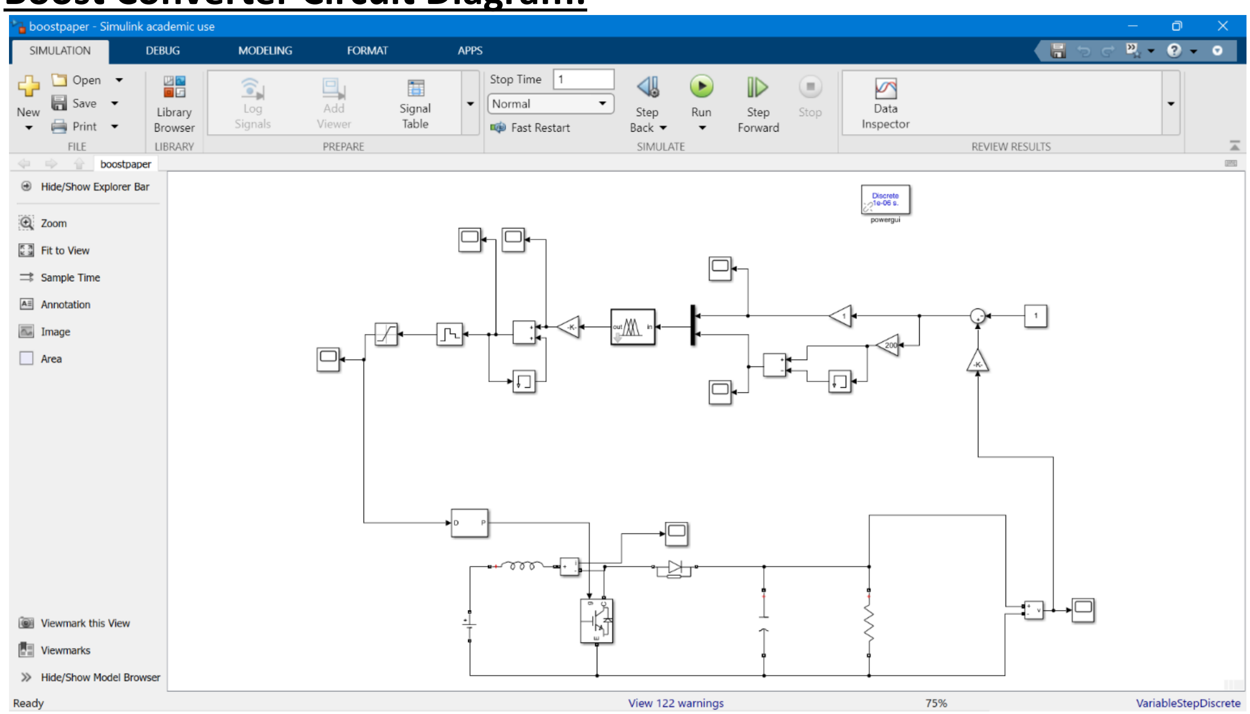
Similarly, zero and negative error rules can be inferred. More expanded rules are based on these rules. Table II shows a prepared fuzzy rule base that establishes a relationship between a collection of inputs and outputs. As stated in table II, a certain combination of inputs (error e(n) and rate of change in error e(n)) corresponds to a specific output (change in duty cycle d), for example, if the error is NS and the rate of change in error is PB, it corresponds to ZE change in duty cycle. This serves as the foundation for the construction of the membership function of error e(n), rate of change in error e(n), and change in duty cycle d, as illustrated in Figure-4. Membership values are determined with efficiency, time to steady state, overshoot, and ripples in consideration. For example, if somehow the magnitude of the PB output (perturb in duty cycle) of the FLC is relatively tiny, adding such a perturb will require more time to follow the reference value than adding a larger perturb. Perturb cannot be of extremely great scale since it would result in a huge and unfavourable overshoot. Once the intended FLC is implemented, the membership values determine the performance; it may not be as accurate as needed; modifying membership functions is a complex procedure; gains may quickly adjust the membership values, and therefore the total performance can be improved. Gain values may vary depending on the application. By adjusting the gains, the inputs and outputs of the FLC may be accurately adjusted for optimal tuning to get the required output.

<u>CIRCUIT DESIGN – DC DC Converters</u>

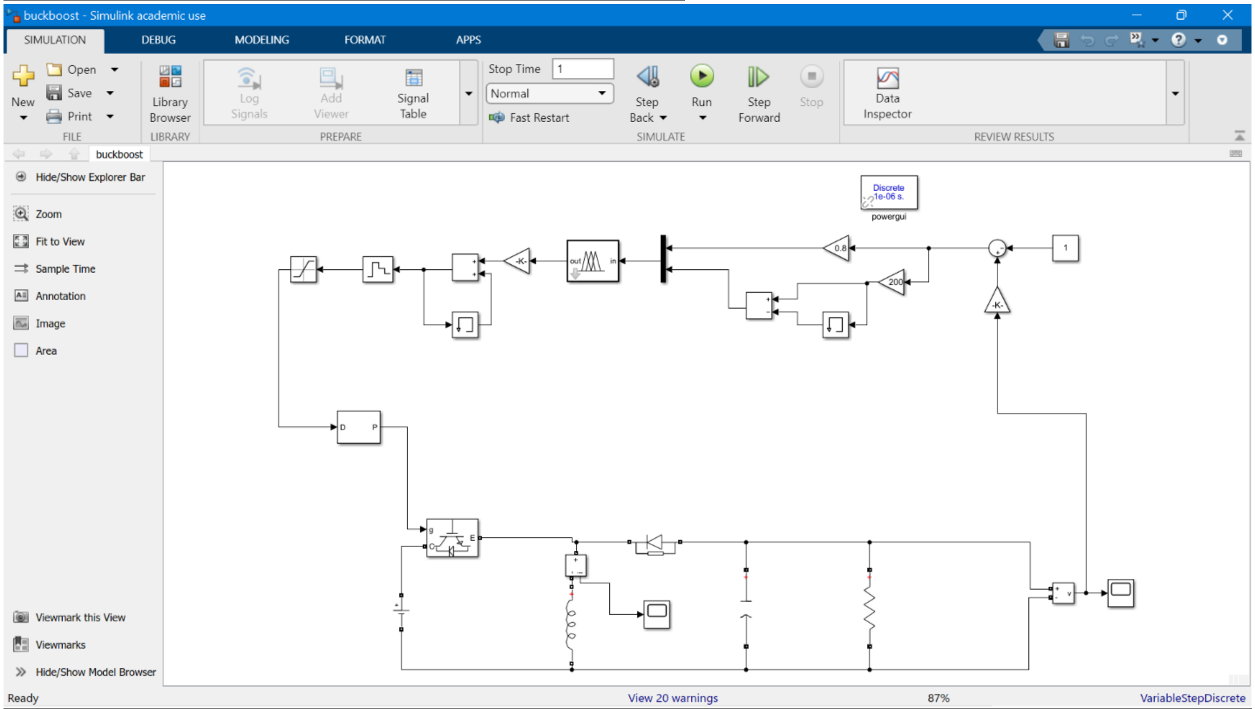
<u>Buck Converter Circuit Diagram:</u>



<u>Boost Converter Circuit Diagram:</u>

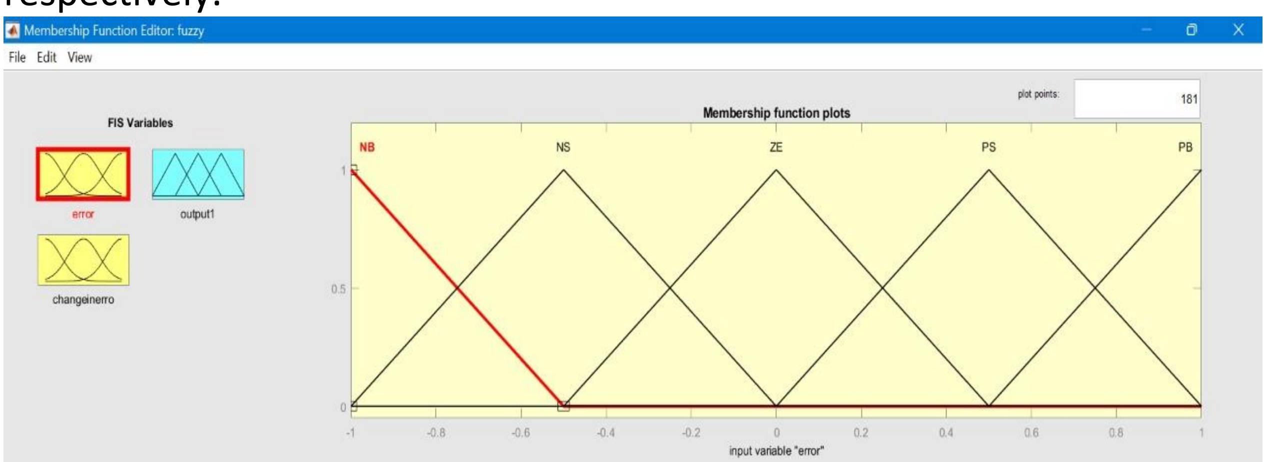


Buck-Boost Converter Circuit Diagram:



Results of Simulation

This section displays steady-state and transient simulation results for varied input voltages and loads. Figures (6), (7), and (8) depict steady-state FLC operation for converters buck, boost, and buck-boost, respectively.



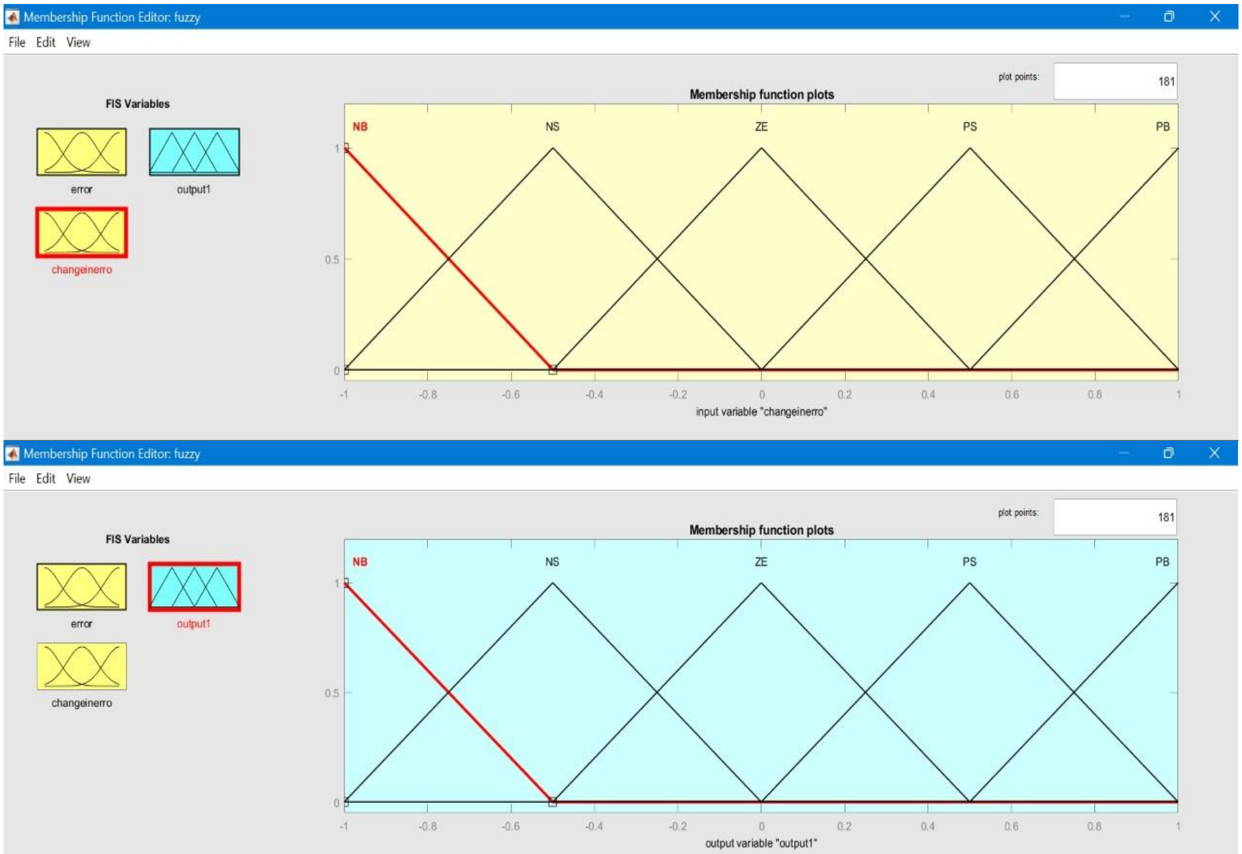


Figure-5: A general membership function is provided for (a) error, (b) error change, and (c) duty cycle.

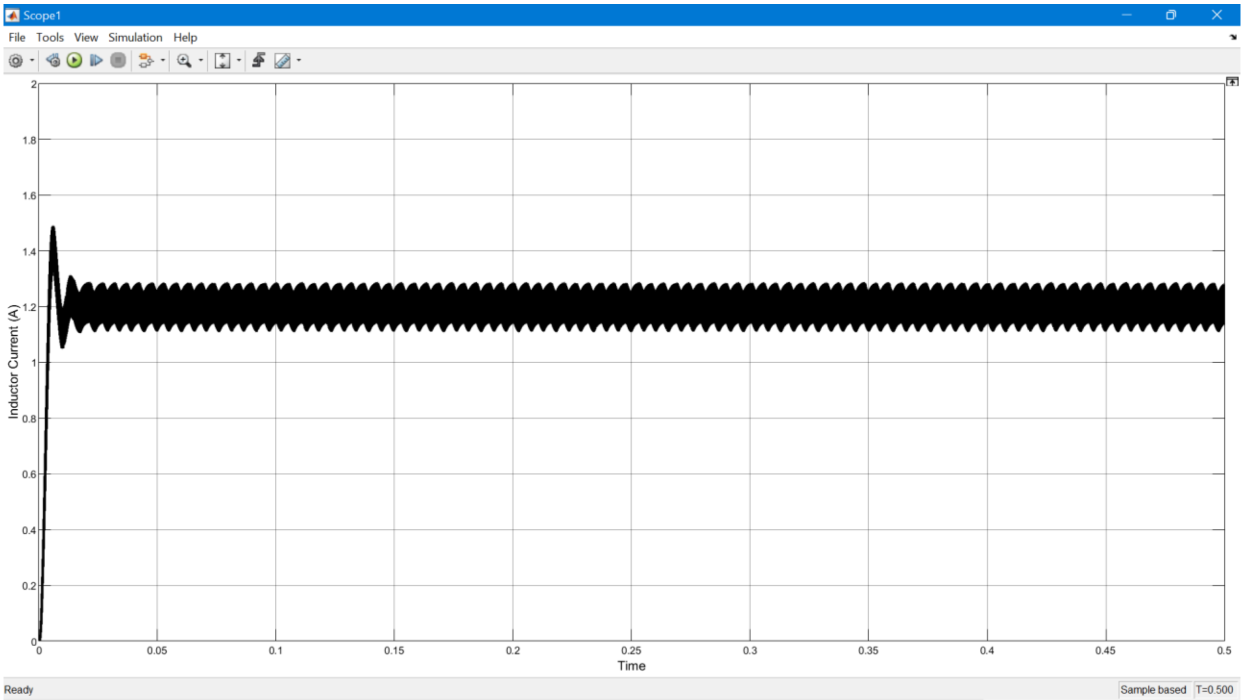
TABLE II: The fuzzy rule base that defines the relationship between input and output

error/change in error	NB	NS	ZE	PS	PB
NB	PB	PB	PB	PS	PS
NS	PB	PS	PS	PS	ZE
ZE	PS	PS	ZE	NS	NS
PS	ZE	NS	NS	NS	NB
PB	NS	NB	NB	NB	NB

The steady-state findings indicate how the system behaves under the conditions for which the converters and controller are intended. The steady-state current and voltage ripples are within the design limits. When exposed to a common rule base built for all converters, the buck converter reaction displays overshoot and a quick response, indicating that the buck is a more stable system. This demonstrates FLC's ability to maintain the proper output voltage when the input voltage changes abruptly.

Figure-6: Buck Converter Results in the Steady State

(a) Inductor current and ripples:



(b) Output Voltage and ripples:

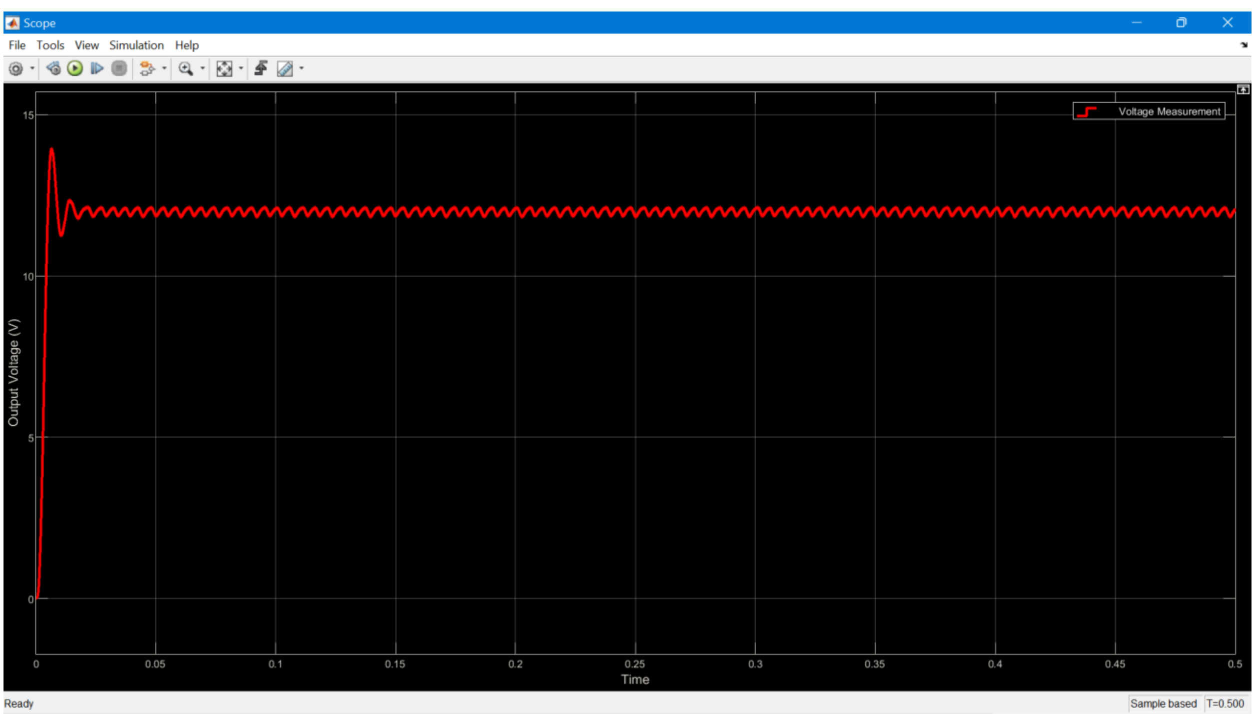
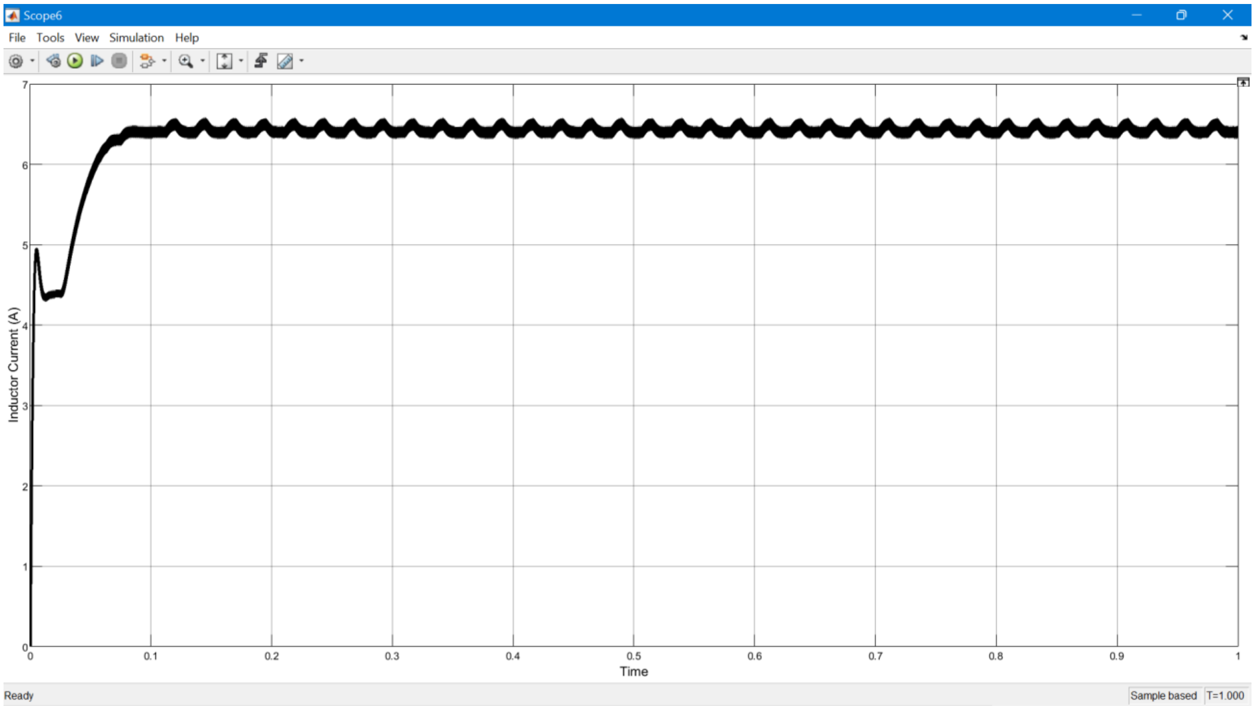


Figure-7: Boost Converter Results in the Steady State

(a) Inductor current and ripples:



(b) Output Voltage and ripples:

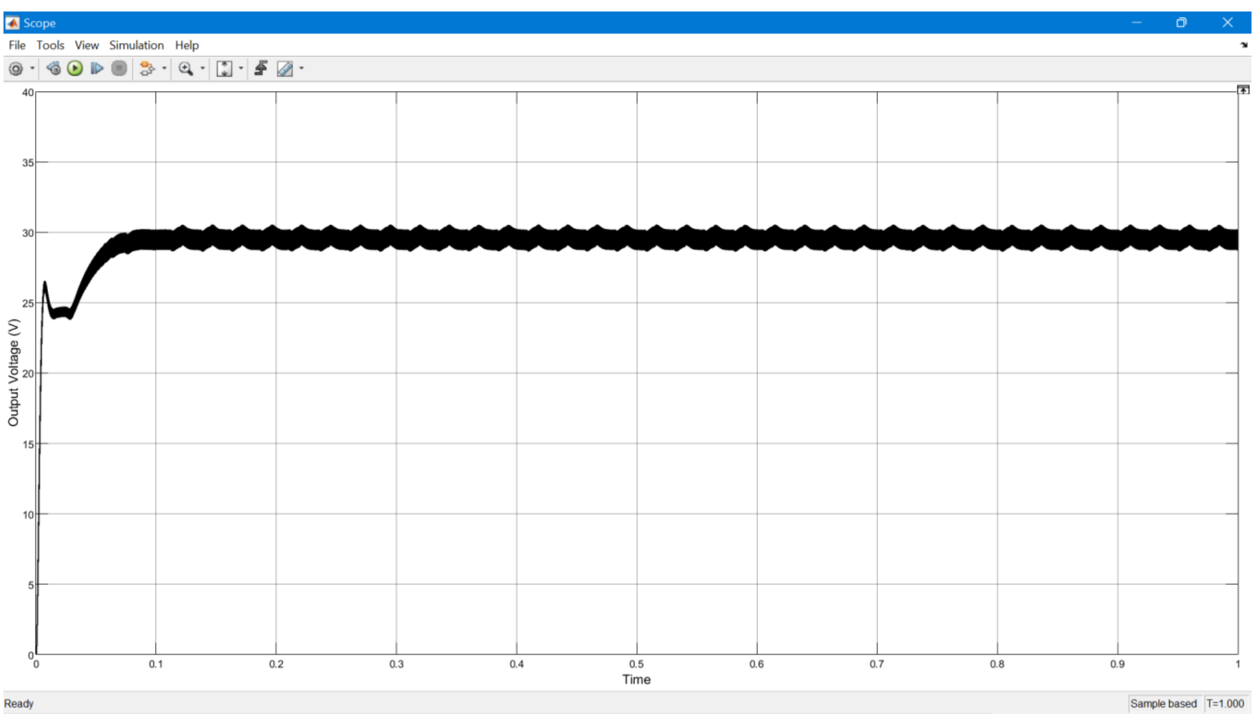
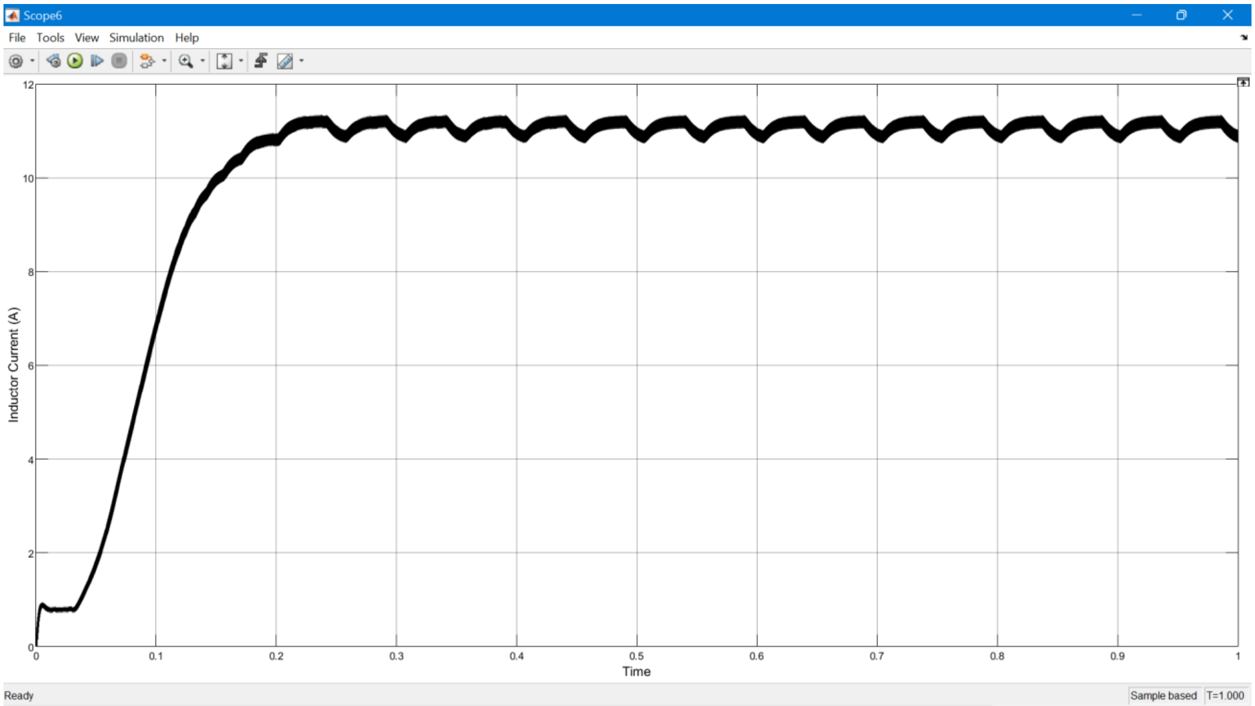
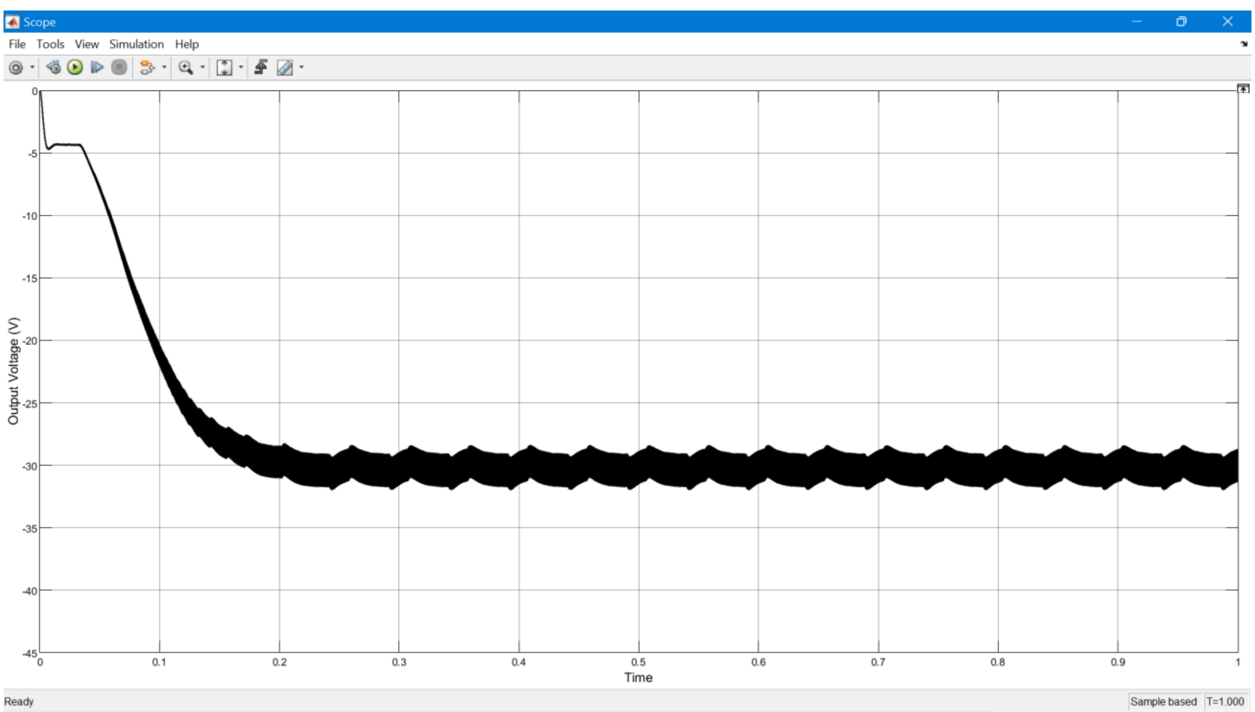


Figure 8: Buck-Boost Converter Results in the Steady State

(a) Inductor current and ripples:



(b) Output Voltage and ripples:

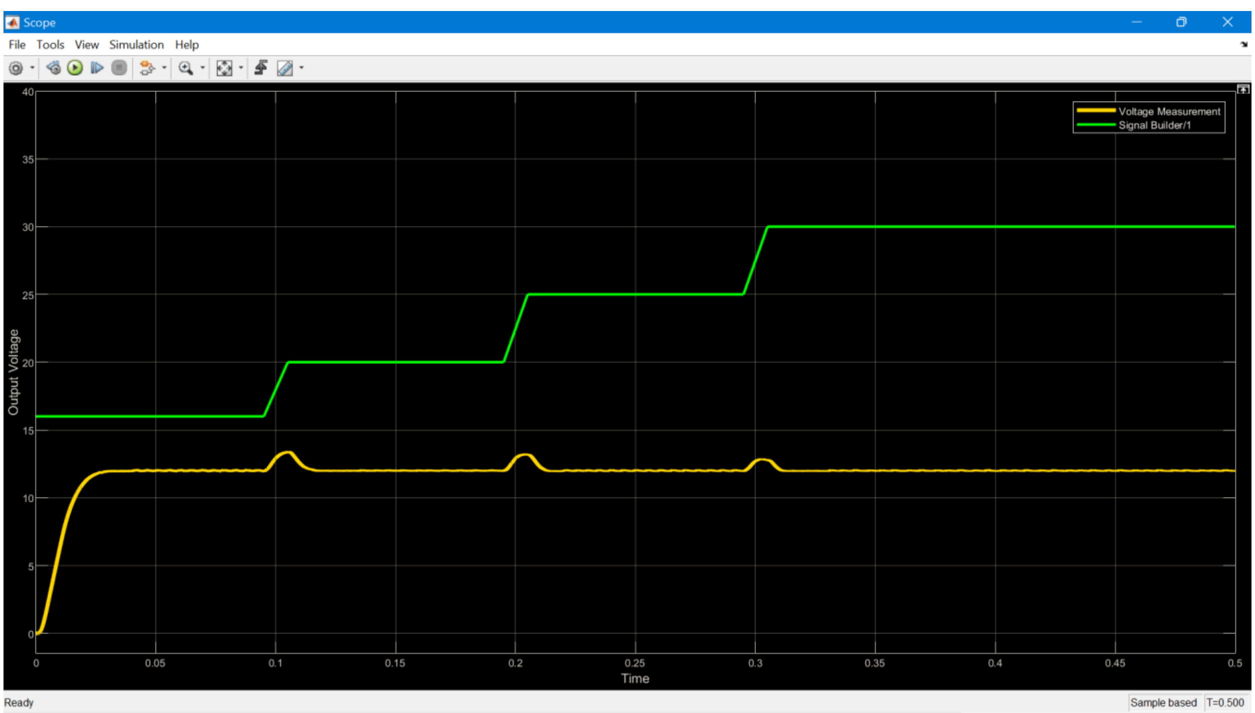


Conclusion & Inferences

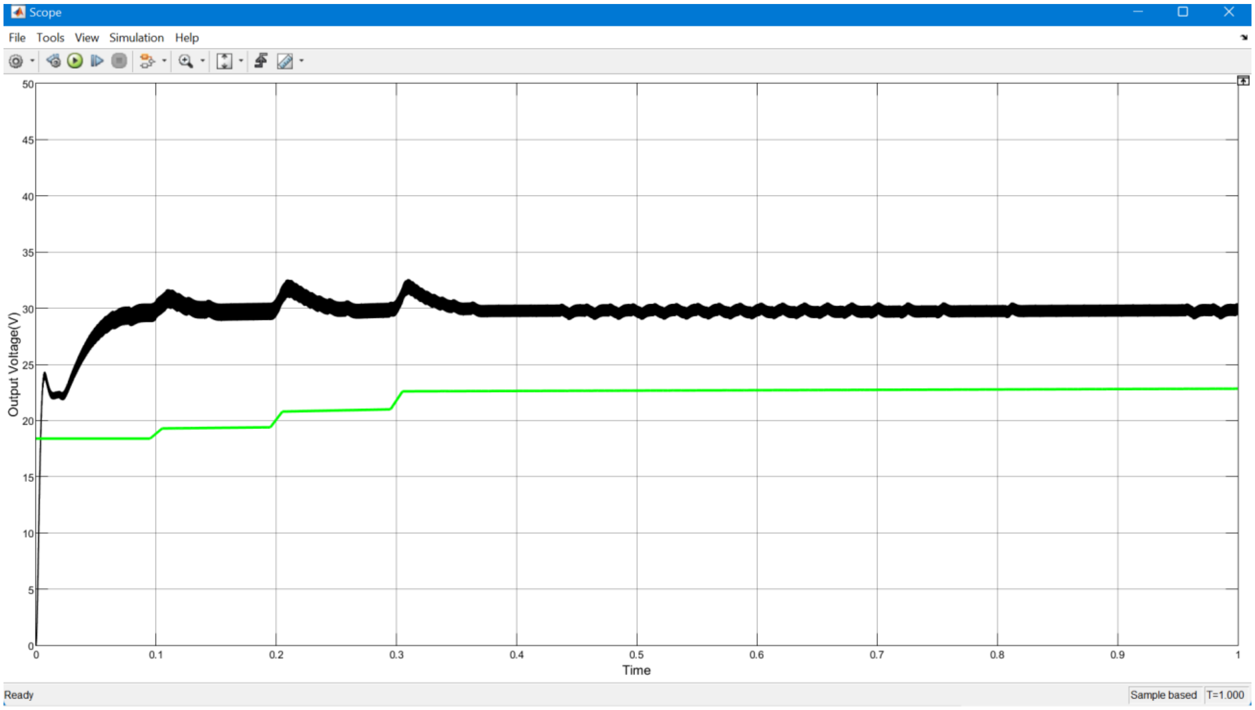
This study demonstrates that a single rule base FLC can be developed for all 2nd order DC-DC converters including just gains adjusted. There is no need for mathematical modelling, which further decreases complexity. The FLC is not sensitive to parameter changes since its functioning is determined by the behaviour of the system rather than by its transfer function. It operates in a stable condition. This investigation demonstrates the noteworthy behaviour of a single controller for buck, boost, and buck-boost converters, as well as its resilience against dynamic supply voltage fluctuation. Its practical implementation is also straightforward when compared to other traditional controllers since it may be built on a basic microcontroller.

Figure-9: System Response to Step Changes in Input Changes

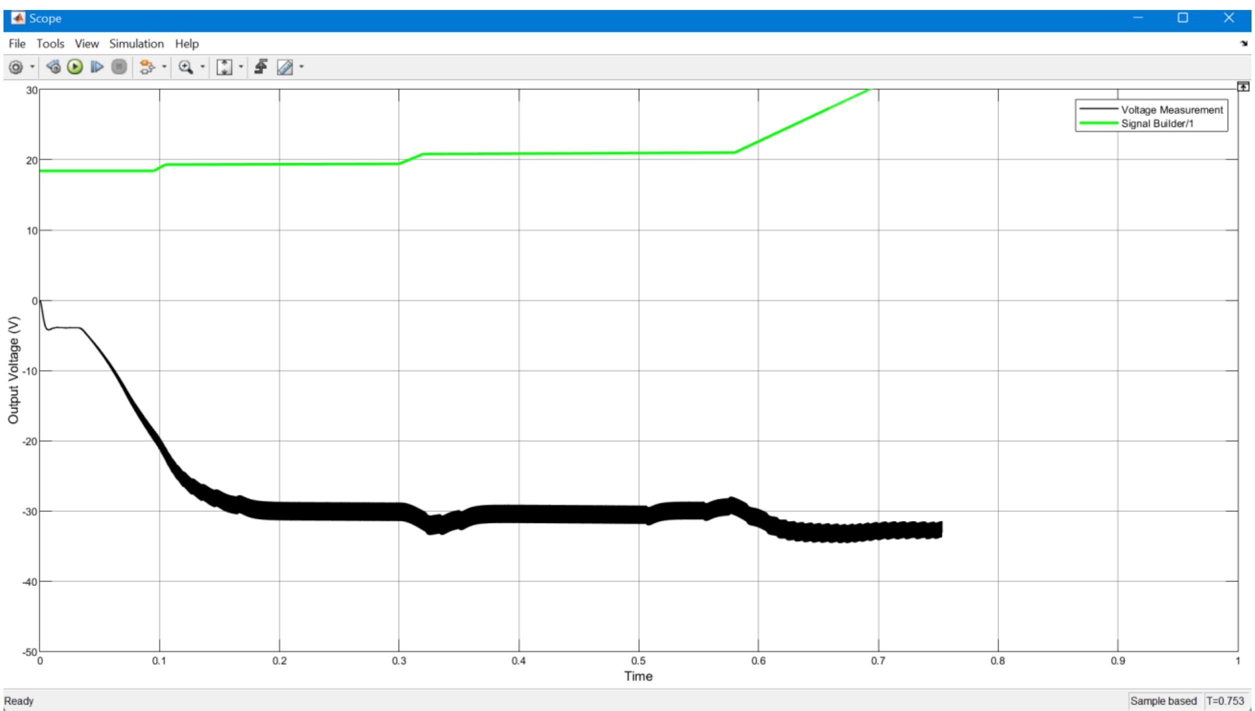
(a) Buck converter:



(b) Boost Converter:



(c) Buck-Boost Converter:



****