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Modeling and Performance of a Buck Converter Based on 'Fuzzy Logic Soft Computing Technique' for Low Voltage Operations

C Kitala, N. Oyie, O. Winston

***Abstract** This present paper details a 'fuzzy logic soft computing technique' of designing a controller for a buck converter operating at low voltages. The dc - dc buck converters find applications in solar energy technologies where they are used in solar control charging systems, battery charging systems, drones, in the automotive industry where there is integration of the engine and dc-dc motor drives resulting in hybrid electric drives or vehicle's. Conventional controllers that is the proportional derivative control (pid) have dominated the control engineering field from the time of invention, however, these controllers present increased overshoot and a long time to achieve steady-state conditions. In this regard since fuzzy logic has intelligent capabilities, then a fuzzy logic soft computing-based controller is proposed in this paper. A mathematical analysis of the dc-dc buck design is also given and the modeling of the fuzzy logic control algorithms that avoids mathematical analysis is also discussed. Fuzzy control is one of the soft computing tools that consists of the observation made by people and their decision based on non-numerical information is also discussed. The performance analysis of the fuzzy controller is determined under constant load and variable decreasing voltage conditions. The analysis and simulation of the dynamic response in closed-loop frequency response are conducted in the Simulink platform in Matlab. The proposition of control is executed on a dc-dc step down converter for an input of 12V. This proposed fuzzy logic control technique provides a dc – dc buck converter system with increased overall operating efficiency and a very stable output.*

***Keywords:** Modeling, Buck Converter, Performance, Fuzzy Controller, Fuzzy Algorithm*

I. INTRODUCTION

An electronic power converter is an electronic circuit designed for the energy conversion process. It can convert a dc voltage from one level to another [1] Electronic power buck converters are designed to have a decreased output voltage compared to the input voltage. Electronic power buck converters are also designed to operate at high efficiency [2]. This attribute and the advancement in semiconductor technology, which has led to the mass production of cheap semiconductor devices, have contributed significantly to lowering the cost of constructing electronic power buck converters. When designing electronic power buck converters that operate in the open-loop control configuration, instability tends to affect the devices and manifests itself through overshoot/undershoot, high settling time, and steady-state errors [3]. This problem can be overcome by modeling the converter in a linear fashion. Linear control methods, such as the P, I, D, PID, can be applied when designing the controllers [4] [5].However with PID even after rigorous mathematical analysis there is increased overshoot at low voltage applications. With the advancement in computational intelligence and engineering techniques, various control platforms have emerged, including the fuzzy logic control that features totally different control design considerations and concepts. Fuzzy control forms part of soft computing techniques and does not require accurate mathematical models. It requires effective linguistic variables [6]. Fuzzy control techniques can provide a control scheme with high optimal performance in electronic engineering applications [7] [8].The diagram of an electronic power buck converter for low voltage applications is shown in fig. 1. The alternating current supply is first converted to direct current using a single-phase half-wave rectifier. The output of the rectifier then becomes the input to the buck converter. Additionally, the output of the ac-dc converter can have alternative connection made to accept dc voltage from storage batteries or can charge a battery. The buck converter steps down the input voltage to supply the load resistance R. Taking into consideration the open-loop design configuration and the closed-loop design when modeling converters [3], the Simulink results using the matrix laboratory/Simulink platform [9] of the buck converter are also discussed. This study models a method that eliminates the overshoot and almost zero rise time in buck converters

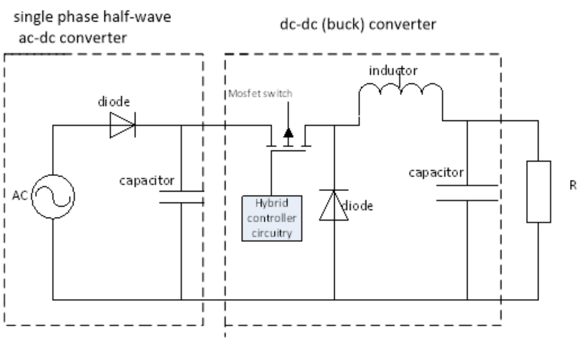

Fig. 1.Diagram of an electronic power buck converter circuit

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II. NOVELTY OF THIS STUDY

The objective of this research study is modeling and perform an analysis of a fuzzy logic controller for an electronic power buck converter for constant load-variable low voltage operations where the soft computing technique is the main criteria for designing a buck converter with good performance.

With the ever-changing technology, soft computing presents a platform that is based on artificial intelligence or real intelligence which determines and applies the normal human thought process. Soft Computing has and still is an emerging field with many applications in the engineering fields as well as in humanities as it is tolerant of uncertainty and partial truth Soft computing avoids rigorous mathematics and applies human-like decisions.

It thus provides a quick and cost-effective solution in the design of electrical/electronic engineering systems hence it lends a platform for novelty, especially for engineering students.

III. OPERATION OF BUCK CONVERTER IN CONTINUOUS CONDUCTING MODE

Fig. 2 shows a diagram of dc-dc buck converter, where the operation is mainly determined by the changes in the charge stored in the inductor L. When the MOSFET switch is ON the inductor is charged and stores energy in electromagnetic form.

During OFF time the inductor discharges. In continuous conducting mode, the current does not reach zero but flows continuously as shown in the waveforms in fig. 3(c). When MOSFET switch is on, current through the inductor rises linearly and when off current decreases.

This current alternates between a maximum value I_{MAX} (on time) and minimum value I_{MIN} (off time).This gives a switching duty cycle D of;

$$D = \frac{T_{ON}}{T_{ON} + T_{OFF}} = \frac{V_{OUT}}{V_{IN}}$$

$$V_{OUT} = DV_{IN}$$

Where D is the duty cycle, T_{ON} is the on time, T_{OFF} is the off time, V_{IN} is the input voltage and V_{OUT} is the output voltage.

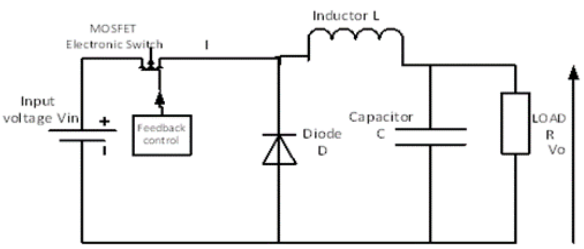

Fig. 2.. Schematic diagram of a buck converter

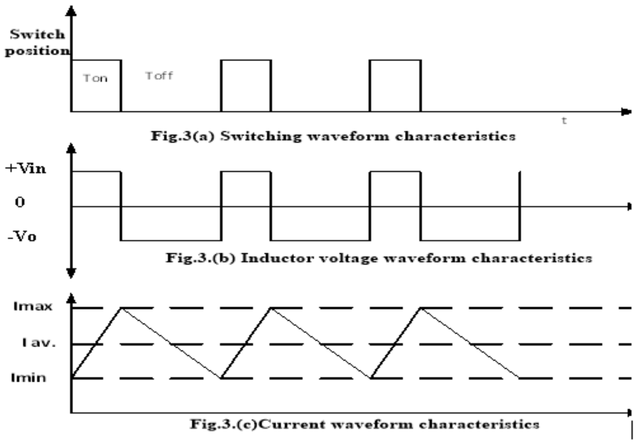

Fig. 3.Output waveforms

IV. MATHEMATICAL ANALYSIS (MODELLING) AND COMPONENT SIZING

A. Analysis and component sizing

When the switch (in fig. 2) is ON [10] [11] then current flows through inductor, diode is reverse biased and does not conduct. Applying Kirchhoff's voltage law;

$$V_{IN} - V_{OUT} = L\frac{dI}{dt} \quad (1)$$

Where L is the inductance of the inductor and $\frac{dI}{dt}$ is the rate of change of the current in the inductor.

Current I in the inductor keep changing from one value to another that is maximum value to minimum value in time dt then;

$$dI = \Delta I = I_{MAX} - I_{MIN} \quad (2)$$

Where I_{MAX} is the maximum value of current, I_{MIN} is minimum value of current and ΔI is the change in current in the inductor and change in time is,

$$dt = t_1 \quad (3)$$

Where t_1 is time the mosfet switch is on

Therefore,

$$V_{IN} - V_{OUT} = L\frac{\Delta I}{t_1} \quad (4)$$

And the time t_1 can be given by,

$$t_1 = \frac{L\Delta I}{V_{IN} - V_{OUT}} \quad (5)$$

When the switch (MOSFET) is OFF the voltage across the inductor changes polarity, then,

$$-V_{OUT} = -L\frac{\Delta I}{t_2} \quad (6)$$

Where t_2 is the off time. The time t_2 can then be given by,

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$$t_2 = \frac{L\Delta I}{V_{OUT}} \quad (7)$$

The total time T for on time and off time is given by equation (8)

$$T = t_1 + t_2 = \frac{L\Delta I.V_{IN}}{V_{OUT}(V_{IN} - V_{OUT})} \quad (8)$$

From equation (8) and applying the equation for the duty cycle then, change in inductor current is given by equation (9)

$$\Delta I = \frac{V_{IN}D(1-D)}{Lf} \quad (9)$$

Where f is now the switching frequency.

The average current in the capacitor I_C is,

$$I_C = \frac{\Delta I}{4} \quad (10)$$

The voltage across the capacitor C is

$$V_C = \frac{1}{C}\int I_C dt$$

Giving $$\Delta V_C = \frac{\Delta I}{8f^2C} \quad (11)$$

Substituting for ΔI in equation (11) then change in voltage across the capacitor is given by,

$$\Delta V_C = \frac{V_{IN}D(1-D)}{8Lf^2c} \quad (12)$$

Most low-power electronic devices have a power rating circuit impedance of 4-8 ohms and a current rating range of 0.5-2 amperes, with dc power sources rarely exceeding 12 volts d.c. In this paper, the following research/study delimitations/ parameters are considered; $V_{IN} = 12V$,output resistance/impedance=4ohms, and output current=2 amps and switching frequency of 60 kHz.

Change in inductor current and capacitor voltage is taken as: ΔI *and* ΔV_c *as 6% and 2.5% ripples* respectively.

Then the required value of the inductor L can be determined at $I_{out} = I_L$=2amps, which is the maximum output current.Then the change in inductor current is given by,

$$\Delta I = \frac{6}{100} \times 2 = 0.12amperes$$

From equation (9) the inductance is given by,

$$L = \frac{12 \times 0.5 \times (1-0.5)}{0.12 \times 60 \times 10^2} = 417.8\mu H \quad (13)$$

For a load of 4ohms and maximum load current of 2amperes then the output voltage is,

$$V_{OUT} = R_{load} \times I_{load} = 4 \times 2 = 8Volts$$

Therefore the change in capacitor voltage is;

$$\Delta V_C = \frac{2.5}{100} \times V_{OUT} = \frac{2.5}{100} \times 8 = 0.2Volt$$ and the required value of the capacitor C is determined from equation (12) as,

$$C = \frac{12 \times 0.5(1-0.5)}{8 \times 417.8 \times 10^{-6} \times 0.2 \times (60 \times 10^3)^2} = 1.24\mu F \quad (14)$$

Table 1 shows the summary of considered and designed values.

Table- I: Summary of designed values/parameters

Parameter	**Designed/calculated value**
Input voltage(volts)	12
Capacitor Cmicrofarads	1.25
Inductor L microhenrys	417.8
Proposed Load (constant)resistor/ impedance ohms Ω	4

B. Matlab model of buck converter without controller

Fig. 4 shows a buck converter model in matlab having no feedback control and the simulation results are as shown in table II.

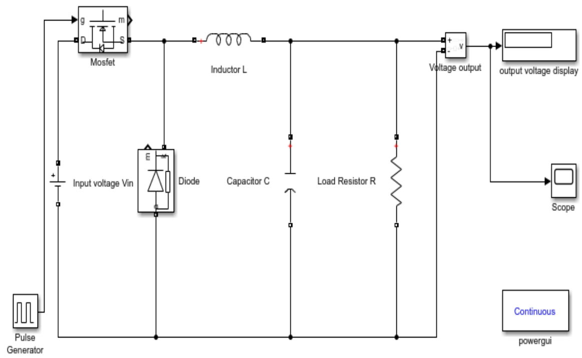

Fig. 4.Diagram of buck converter model with no feedback control

C. Output voltage results without controller

Table- II: Output voltage results without control

Vref	9V	8V	6V	4V	3V
Output voltage with No controller	8.514V	7.568V	5.676V	3.784V	2.838V
Overshoot/ Undershoot	- 0.486	- 0.432	-0.324	-0.216	-0.163

V. MODELING THE BUCK CONVERTER AS A CONTROL SYSTEM

Fig. 5 shows representation of buck converter as a control system. The buck converter is usually a single input single output system (SISO)

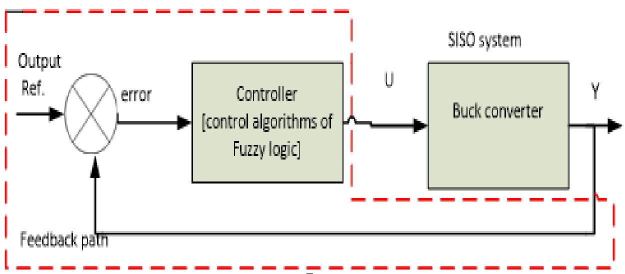

Fig. 5.Diagram of a model of a buck converter control system

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VI. FUZZY LOGIC DESIGN

A. The control algorithm of fuzzy logic and design

The fuzzy control algorithm presents an arranged set of fuzzy instructions that generate an approximate solution to a certain problem when executed [12]. The fuzzy logic design consists of the observation made by people and their decisions based on non-numerical and inexact information. Fuzzy logic imitates decision-made by human beings, which entail all intermediate possibilities between digital values true or false and *'yes'* and *'no'*. Thus, fuzzy logic simulates human reasoning. Fig. 6 shows a proposed diagram of developing a fuzzy logic control algorithm**.** The algorithm consists of observation and the decision made during a step response of the buck converter and the implied logic. The logic response is divided into seven regions. The deviation of the system's response can be viewed as an error, which can be said to be negative big, negative medium, negative small, zero, positive small, positive medium, and positive big.

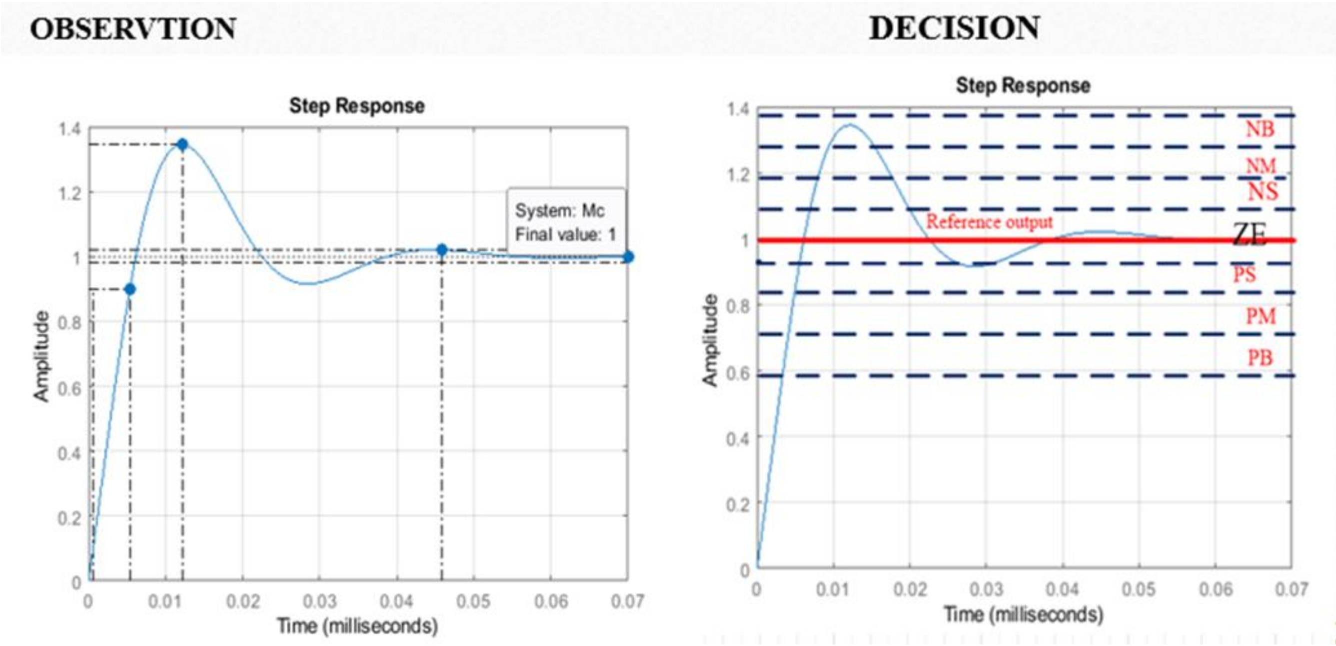

Fig. 6.Diagram of developing a fuzzy logic control algorithm

B. Fuzzy logic input variables

The control algorithm input variables are the error value determined through the comparison method, which involves the output voltage desired and the reference voltage. Hence, error value ev(k)=Vref,-Voutput, and change in error value will be a comparison of the present error with the previous value of error. [13] [14] Essentially, change in error value cev = ev(k) - ev(k-1), where ev(k-1) is the value of the previous error. In this study, the output voltage range considered is from 3 volts to 9 volts; thus, the reference voltages will be from 3 to 9 volts.

C. Fuzzy membership functions and fuzzy logic rules base control algorithm.

The step response has been divided into seven regions, thereby giving seven membership functions. The fuzzy sets are have been defined as: NB-Negative Big, NM-Negative Medium, NS-Negative Small, Z-Zero, PS-Positive Small, PM-Positive Medium, and PB-Positive Big and the seven regions give a 7 by 7 cross matrix shown in table III, thereby resulting in 49 rules and the output is the duty cycle ratio. The top row of the matrix indicates fuzzy set variables **e**, which is the error. The left column indicates **ce,** change in error. The body of the matrix indicates the output variable of the membership functions, which is the duty ratio that can vary from 100% to 0%

Table III. 7*7 cross rule matrix

e / Ce	NB	NM	NS	ZE	PS	PM	PB
NB	*NB*	*NB*	*NB*	*NB*	*NM*	*NS*	*ZE*
NM	*NB*	*NB*	*NB*	*NM*	*NS*	*ZE*	*PS*
NS	*NB*	*NB*	*NM*	*NS*	*ZE*	*PS*	*PM*
ZE	*NB*	*NM*	*NS*	*ZE*	*PS*	*PM*	*PB*
PS	*NM*	*NS*	*ZE*	*PS*	*PM*	*PB*	*PB*
PM	*NS*	*ZE*	*PS*	*PM*	*PB*	*PB*	*PB*
PB	*ZE*	*PS*	*PM*	*PB*	*PB*	*PB*	*PB*

D. Membership functions and Implementation in MATLAB

Membership functions: Each element in a membership function in the universe of discourse can have a numerical value or even a zero value. This degree of membership of elements in the universe of discourse describe a fuzzy set. The most common membership function are trapezoidal, triangular and bell-shaped functions [15] [16]. In this study, the triangular membership function has been selected in the FIS toolbox. This membership function is characterized by 3-parameters a, b, c which represent the X-coordinates of the 3-vertices in a fuzzy set.

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a and b represents the lower boundary and the upper boundary respectively in which the degree of membership functions are zero and b represents the centre where degree of membership function is maximum that is 1as shown in fig. 7(a) [17]. The curve of the membership function is a function of a vector, x, which depends on the 3- parameters a, b and c as given by;

U(x) = 0, x< a or x > c

At X = a, b

$$U_{(X)} = \frac{x-a}{b-a}, \quad a \leq x \leq b$$

At X = b, c

$$U_{(X)} = \frac{c-x}{c-b}, \quad b \leq x \leq c$$

$$U_{triangle}(X; a, b, c) = \begin{cases} 0, & x < a \\ \dfrac{x-a}{b-a}, & a \leq x \leq b \\ \dfrac{c-x}{c-b}, & b \leq x \leq c \\ 0, & c < x \end{cases}$$

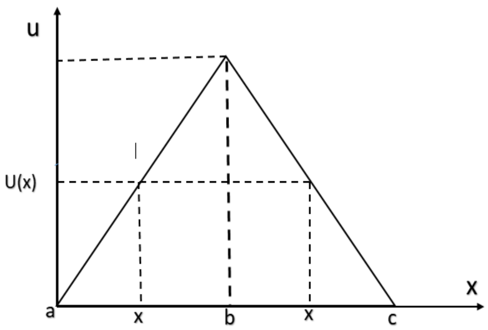

Fig. 7. (a) Triangular membership function

Fig. 7(b), 7(c) and 7(d) shows membership functions for error, change in error and % duty respectively as implemented in matlab using the fuzzy inference system using 7 triangular membership functions

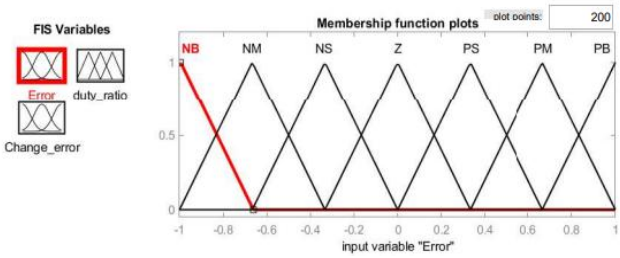

Fig. 7. (b) Membership functions for the error

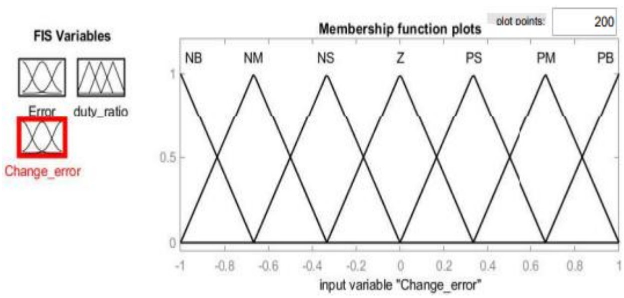

Fig. 7. (c) Membership functions for the change in error

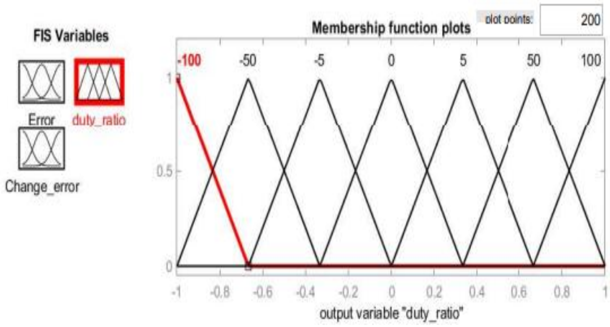

Fig. 7. (d) Membership functions for the %duty

E. Elements of fuzzy logic control

A fuzzy logic control comprises four main elements [18]:

Fuzzification element: If Z is the universe of discourse (fig.8), then fuzzification can be said to be the mapping of an observed input to fuzzy sets [17] [12] [19]. This element converts specific degrees of membership functions of fuzzy sets from crisp input values.

Knowledge base: This element consists of two component parts;

a) Expert knowledge-This consist of rules organized in the form IF…THEN. Each segment of IF and THEN statements are logically connected by the logical operations AND, OR, and NOT which are used in drawing the inference. Each rule has two parts; the antecedent IF defining impressiveness of the system states and consequent THEN which determines the action that the system should undertake to correct state conditions.

b) Data base-This is an organized set of data, facts, statements and conclusions that support expert knowledge. The data base provides the requisite information to other parts of the system allowing them to function as required.

Inference engine: This element interprets, does calculations, rules aggregation and evaluates facts in the knowledge base so as to obtain a controlled action [18].

Defuzzification: This element performs the process of representing a fuzzy set with a crisp value which can be used to perform the required control function [20]. There are many methods of defuzzification. In this study the centroid method of defuzzification is applied in matlab simulations [21]. The Centre of area method calculates the center of area of a fuzzy set and then gives the crisp value.

F. Centroid defuzzification method

This is the most widely accepted of all defuzzification methods as proposed by Sugeno [22] [23].In this method there are areas of two or more contributing rules that overlap and the overlapping area is counted once as shown in fig. 8.

$$\text{Therefore the defuzzified crisp value} = \text{Zout} = \frac{\int U_{out.}(Z).Zd_z}{\int U_{out.}(Z).d_z}$$

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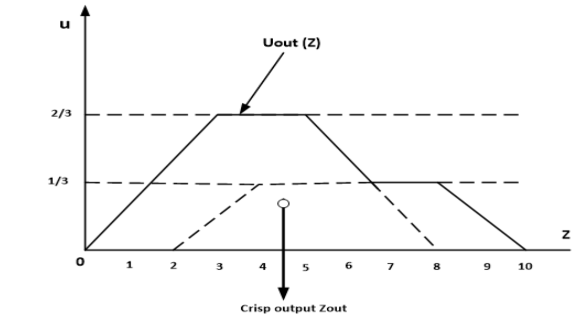

Fig. 8.Defuzzification of output of a two rule system

G. Fuzzy logic control model in MATLAB and simulation results

Fig. 9(a) shows buck converter fuzzy logic controlled model in MATLAB and the corresponding simulation results in MATLAB at 9v, 8v, 6v, 4v, and 3v

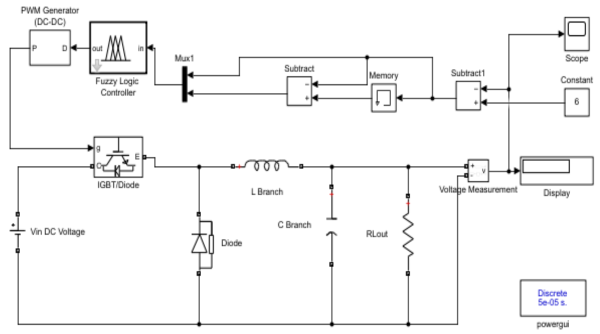

Fig. 9(a) Diagram of fuzzy logic controlled buck converter model in MATLAB

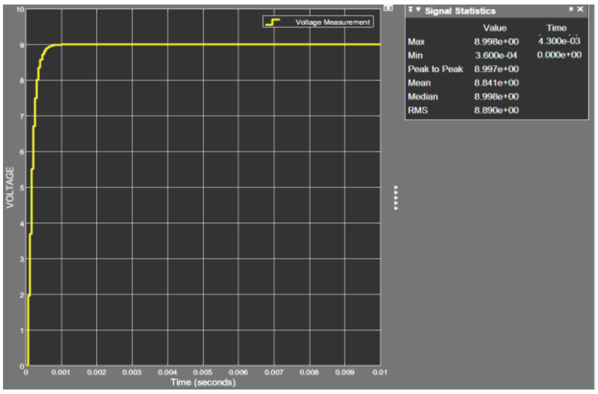

Fig. 9 (b) Response at 9v

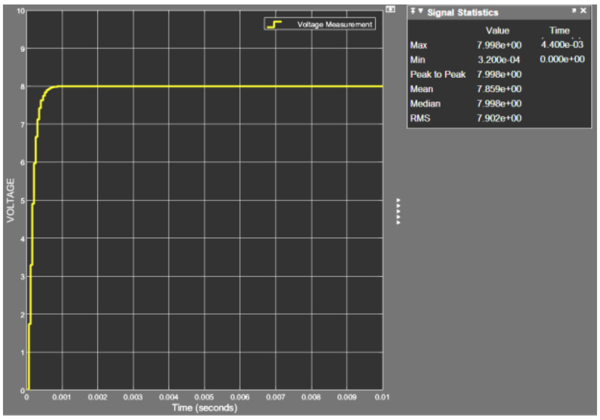

Fig. 9(c) Response at 8v

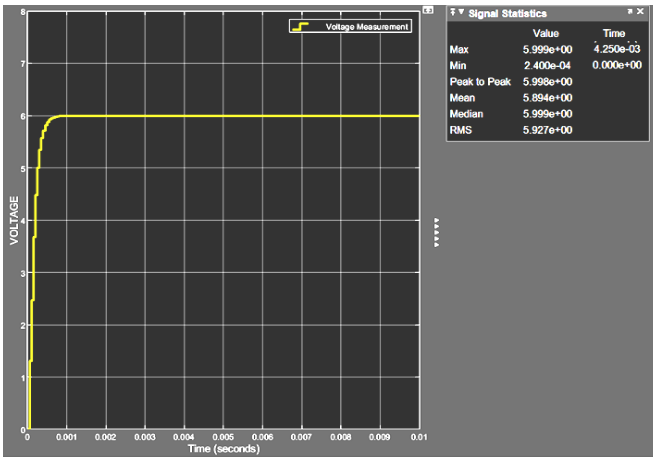

Fig. 9(d) Response at 6v

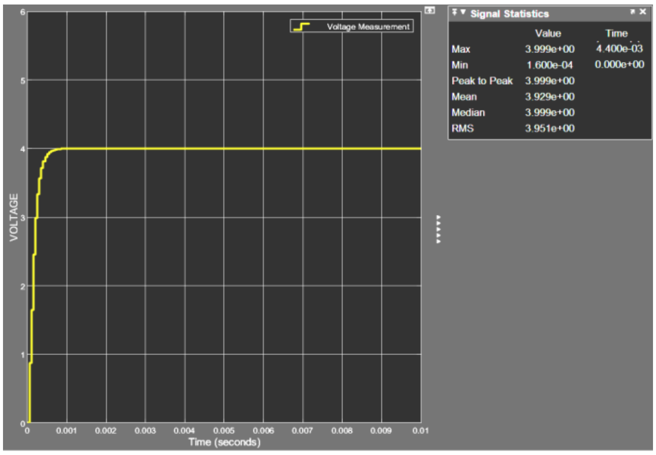

Fig.9 (e) Response at 4v

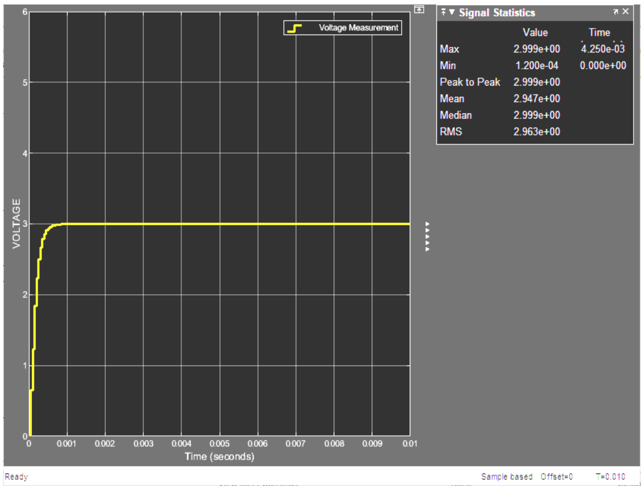

Fig. 9(f) Response at 3v

VII. RESULTS AND DISCUSSION

A. Results

Table IV shows the performance metrics, output voltage, rise time, and overshoot/undershoot simulation result

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Table- IV: Simulation results in real-time in MATLAB Simulink platform for a constant load of 4ohms

Reference voltage V_{ref}	Output with No controller		Output with Fuzzy control		
	Output voltage	Over-shoot	Output voltage	Over-shoot	Rise time (seconds)
9	8.514	- 0.486	8.998	- 0.002	$4.350X10^{-3}$
8	7.568	- 0.432	7.998	- 0.002	$4.350X10^{-3}$
6	5.676	- 0.324	5.999	- 0.001	$4.250X10^{-3}$
4	3.784	- 0.216	3.999	-0.001	$4.350X10^{-3}$
3	2.838	-0.162	2.999	- 0.001	$4.250X10^{-3}$

B. Results discussion

With no controller the buck converter is characterized by large under-shoot. In fuzzy control, the under-shoot is negligibly small, and the rise time to attain the maximum value is almost constant and negligible small. This shows that fuzzy logic technique can be used to design a stable controller with very good output performance with almost zero overshoot.

VIII. CONCLUSION

This paper studies a controlling technique of the output voltage of a dc-dc buck converter with constant load-variable output voltage requirements. The converter can be used to supply varying voltages from 3v, 4v, 6v, 8v, and 9v loads. The simulation results indicate that including a fuzzy controller in the design of buck converters greatly improves the converter's performance, and a stabilized output from the buck converter is achievable. In fuzzy control, a lot of merits arise given that fuzzy is one of the soft computing techniques. One of the merits is the use of linguistic variables which originate from human thought process. From the tabulated results, fuzzy control (a soft computing technique) can provide a more stable/robust control technique in the design of buck converters for application in low voltage devices, which are ever-increasing. The modeling and simulations of the buck converter have been performed on the MatLab/Simulink platform using simscape components. The program development to evaluate the response was also done in MatLab.

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