FUZZY LOGIC CONTROLLER BASED ĆUK CONVERTER

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ABSTRACT**—***This paper presents the development of a fuzzy logic controller for a single-stage Ćuk converter. First of all a Ćuk converter will be designed and tested using simple PWM based pulse generation technique. Later on, an intelligent controller will be developed which will automatically adjust the duty cycle of the converter according to the demand. DC-DC converters with intelligent controllers can be utilized for smart grid, photovoltaic and motor control applications. The intended application of this paper is DC bus voltage regulation for a smart grid. Moreover, in partial shading conditions, the use of fuzzy logic controller becomes inevitable. The Ćuk converter will be selected for purpose of demonstration in this paper due to its flexible gain and continuous input current. The fuzzy logic controller will then be integrated with this converter. For implementing this controller, the inputs and output variables will be first fuzzified i.e., converted to linguistic variables from crisp values. Heuristic knowledge will then be embedded in the rule base of the controller which will decide the active rules for particular input conditions. Once, the active rules are decided, next step will be the aggregation of these rules. In the last step, the aggregated output will be defuzzified using centroid area method. Results will be validated using mathematical analysis and MATLAB Simulink.*

Keywords— Pulse Width Modulation (PWM), Fuzzy Logic Controller (FLC), Maximum Power Point Tracking (MPPT), Ćuk-converter, smart grid

I. INTRODUCTION

In order to reduce the computational effort, intelligent controllers are replacing the conventional controllers nowadays. Improved performance has been recorded for non-linear controllers as compared to conventional linear PI controllers [1]. Fuzzy logic controllers are among the non-linear intelligent controllers which are also preferred over sliding mode controllers for controlling a DC-DC converter. These controllers effectively resolve the chattering problem introduced by sliding mode controllers [2]. Reduced error, increased efficiency and reduced ripples are the few advantages offered by implanting heuristic knowledge into the system using fuzzy logic controller [2]. It is considered as the simplest of the available controllers for integration with the system and improved response [3]. Maximum power point tracking can be done for photo-voltaic array using DC-DC converter with integrated fuzzy logic controller which takes into account the parametric variations and imprecision in weather variations. During partial shading conditions, maximum power point tracking becomes difficult due to presence of multiple peak points on a photo-voltaic characteristic curve. There is a need of an algorithm which can search for a global power peak instead of local power peaks for avoiding power loss. Reference [4] illustrates the use of fuzzy logic controller for tracking the global power peak point during insolation variations and partial shading situation.

A Ćuk converter will be used in this paper for designing the fuzzy logic controller due to its output voltage flexibility and continuous input current [3]. Energy can be transferred at all irradiation levels by a Ćuk converter with continuous output current [5]. Fuzzy logic controller has been used with a multi-input Ćuk converter in reference [6]. Experiments were conducted on DC-DC converters in order to synthesize the rule base for fuzzy logic controller [7].

The remainder of this paper is organized as follows. Section II illustrates the design of a single-stage Ćuk converter using the conventional PWM based generator. Section III proceeds with the analysis and design of an intelligent controller based on fuzzy logic. Section IV presents the mathematical analysis for the proposed controller in order to show the validation of theoretical and experimental results. Section V shows the integration of the converter with the fuzzy logic controller in MATLAB Simulink environment. Section VI discusses the research trends and future scope of the proposed system along with explanation of simulation results. In Section VII, the author summarizes this paper.

II. PROPOSED SYSTEM USING ĆUK CONVERTER

A Ćuk converter was designed and simulated in MATLAB. Simulink block diagram of converter has been shown in Figure 1 and the design specifications have been listed in Table 1.

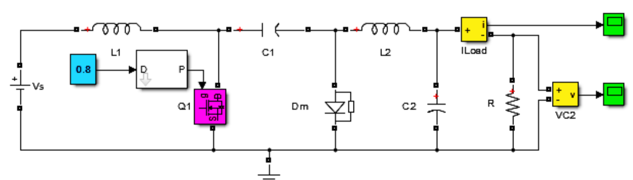

Figure 1: Simulink diagram of single-stage Ćuk converter

Table 1: Design specifications for parameters of Ćuk converter

Name of Parameter	Design Value
Input Voltage	13V
Frequency	50 kHz
Inductor	180 μH
Filter Inductor	150 μH
Capacitor	200 μF
Filter Capacitor	470 μF

When input voltage =13V, duty cycle =0.8, then the converter operates in an open loop condition and in boost mode as duty cycle is greater than 0.5. The output voltage is -34 V and output current is -11A as shown in Figure 2 and Figure 3.

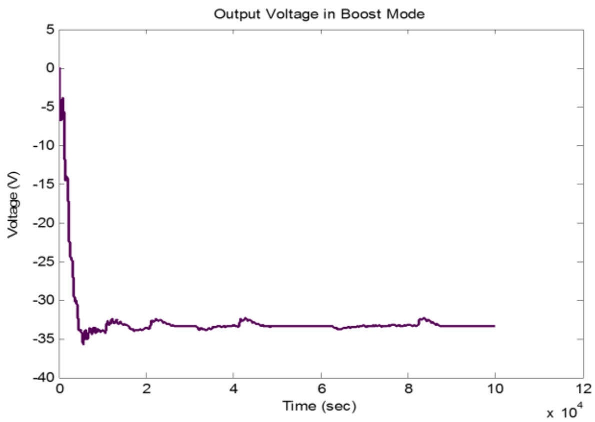

Figure 2: Output voltage in boost mode

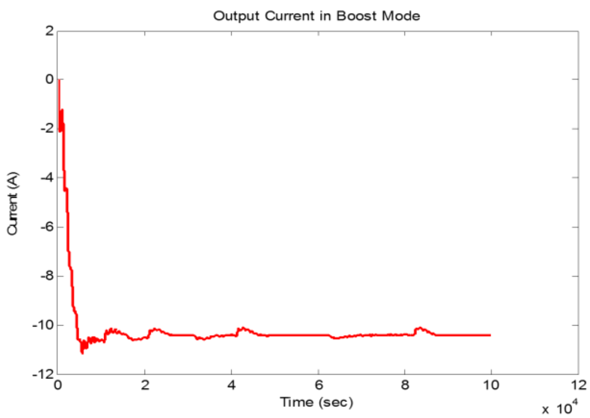

Figure 3: Output current in boost mode

When input voltage =13V, duty cycle =0.3, then the output voltage and output current have been shown in Figure 4 and Figure 5. The converter operates in an open loop condition and in buck mode as duty cycle is less than 0.5.

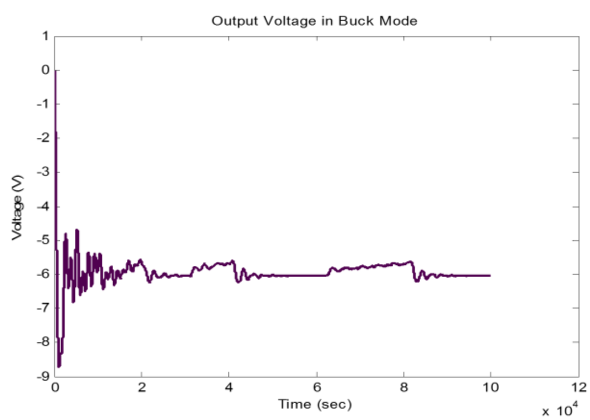

Figure 4: Output voltage in buck mode

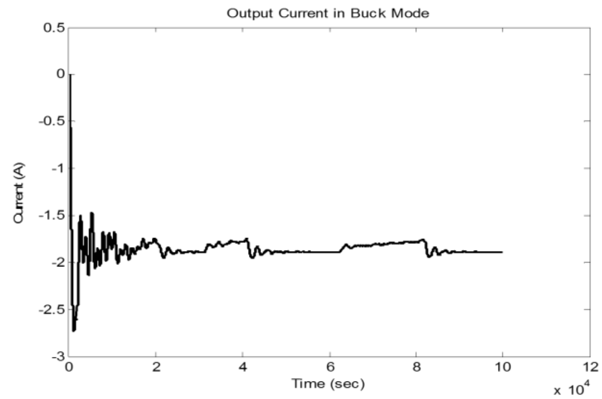

Figure 5: Output current in buck mode

III. FUZZY LOGIC CONTROLLER

In order to implement a fuzzy logic based controller, two inputs are required which are stated below:

$$Error\ (E) = V_{reference} - V_{output} \quad (1)$$

$$Change\ in\ Error\ (\Delta E) = E(k) - E(k-1) \quad (2)$$

The output variable is selected as the duty cycle which is to be controlled in order to keep the voltage at the output equal to the reference voltage. The next step is to determine relationship between inputs and outputs. For example, if output voltage is less than the reference then the duty cycle should be increased. The increment in the duty cycle is basically dictated by the values of error and change in error. If the solution is converging then the value of change in error is not significant. A large value of change in error dictates that solution is diverging and the duty cycle must be changed considerably. Inputs and outputs are first defined in terms of linguistic variables instead of crisp values. These linguistic variables are assigned weights or degree of membership using various membership functions and then rules are defined. The range for "Error" variable is [-4,4] and membership functions defined for this variable are shown in Table 2 and Figure 6. The range for "Change in Error" variable is [-4, 4] and its membership functions are shown in Table 3 and Figure 7. The output variable duty cycle has range [0, 1] and its membership functions are shown in Table 4 and Figure 8. Table 5 illustrate the relationship between input and output fuzzy variables in form of a rule matrix.

Table 2: Membership functions of error

Sr. No.	Name	Type	Range
MF_1	Negative Large	Trapezoidal	[-6.6 -4.1 -3.6 -2.6]
MF_2	Negative Medium	Triangular	[-3.2 -2.4 -1.5]
MF_3	Negative Small	Triangular	[-1.97 1.22 -0.4]
MF_4	Zero	Triangular	[-0.9 0.13 0.78]
MF_5	Positive Small	Triangular	[0.22 1.01 2.09]
MF_6	Positive Medium	Triangular	[1.55 2.3 3.2]
MF_7	Positive Large	Triangular	[2.8 3.6 4.13 7.03]

Table 3: Membership functions of change in error

Sr. No.	Name	Type	Range
MF_1	Negative Large	Trapezoidal	[-6.8 -4.2 -3.7 -2.8]
MF_2	Negative Medium	Triangular	[-3.3 -2.5 -1.6]
MF_3	Negative Small	Triangular	[-2.12 1.3 -0.4]
MF_4	Zero	Triangular	[-0.88 0.12 0.74]
MF_5	Positive Small	Triangular	[0.23 1.00 1.9]
MF_6	Positive Medium	Triangular	[1.55 2.3 3.1]
MF_7	Positive Large	Trapezoidal	[2.7 3.7 4.4 6.29]

Table 4: Membership functions of duty cycle

Sr. No.	Name	Type	Range
MF_1	Very Small	Trapezoidal	[-0.35 0.04 0.155]
MF_2	Medium Small	Triangular	[0.11 0.2 0.3]
MF_3	Large Small	Triangular	[0.25 0.36 0.47]
MF_4	Medium	Triangular	[0.42 0.51 0.61]
MF_5	Medium Big	Triangular	[0.7 0.8 0.91]
MF_6	Large Big	Trapezoidal	[0.86 0.96 1.05 1.45]
MF_7	Small Big	Triangular	[0.55 0.64 0.76]

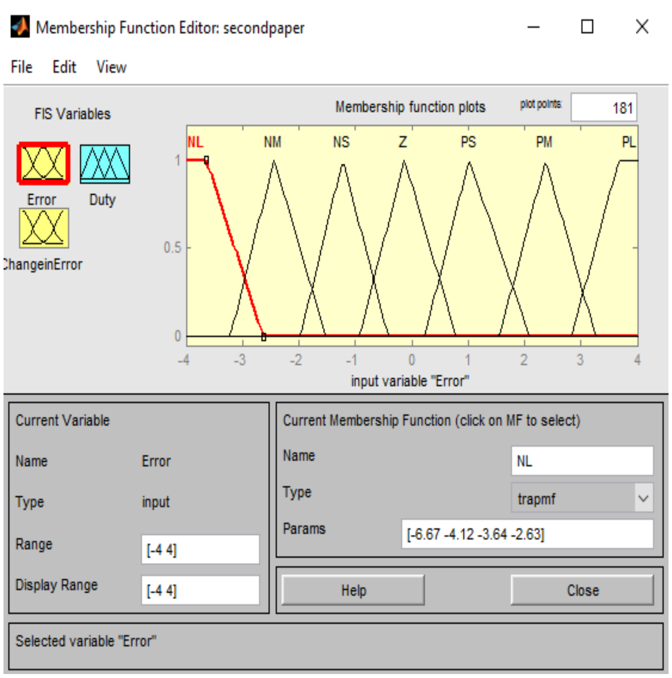

Figure 6: Error membership functions using fuzzy logic designer app (MATLAB)

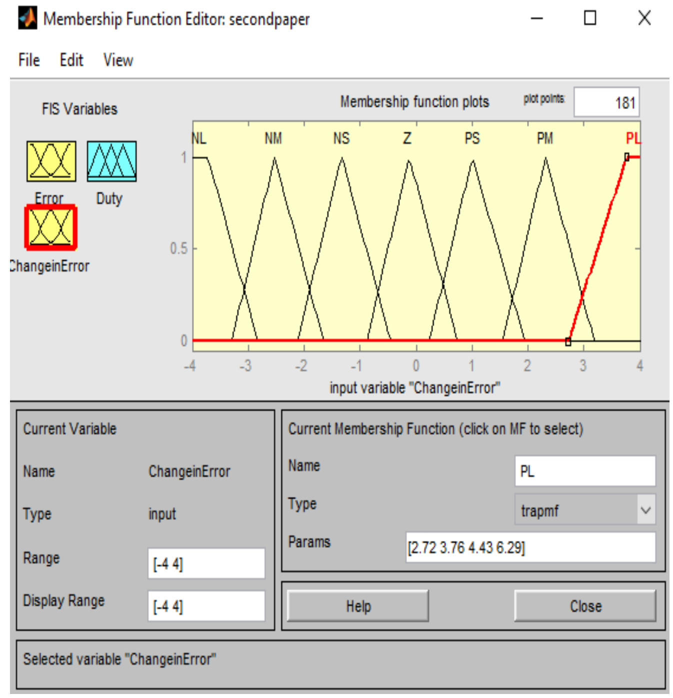

Figure 7: Change in error membership functions using fuzzy logic designer app (MATLAB)

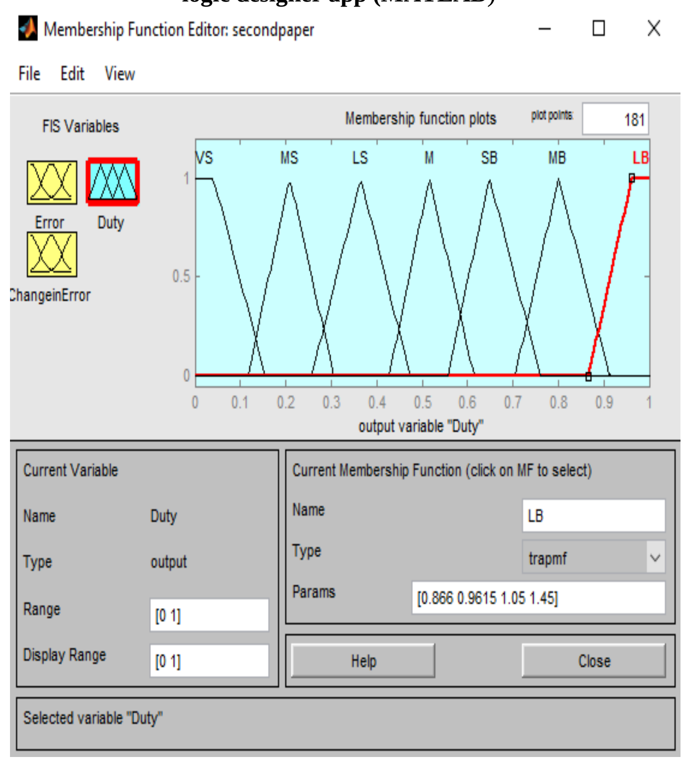

Figure 8: Duty membership functions using fuzzy logic designer app (MATLAB)

Table 5: Rule matrix for fuzzy logic controller

CE /E	NL	NM	NS	Z	PS	PM	PL
NL	Very Small	Very Small	Medi um	Medi um	Mediu m	Medium	Small Big
N M	Very Small	Mediu m Small	Large Small	Large Small	Mediu m	Small Big	Mediu m Big
NS	Medi um Small	Large Small	Large Small	Medi um Small	Small Big	Medium Big	Large Big
Z	Medi um Small	Mediu m Small	Large Small	Medi um	Mediu m	Small Big	Small Big
PS	Medi um Small	Large Small	Medi um	Medi um	Small Big	Small Big	Mediu m Big
P M	Very Small	Very Small	Large Small	Small Big	Small Big	Medium Big	Large Big
PL	Very Small	Very Small	Very Small	Medi um Big	Large Big	Large Big	Large Big

After defining the rules, the surface view in the '*fis*' editor has been shown in Figure 9.

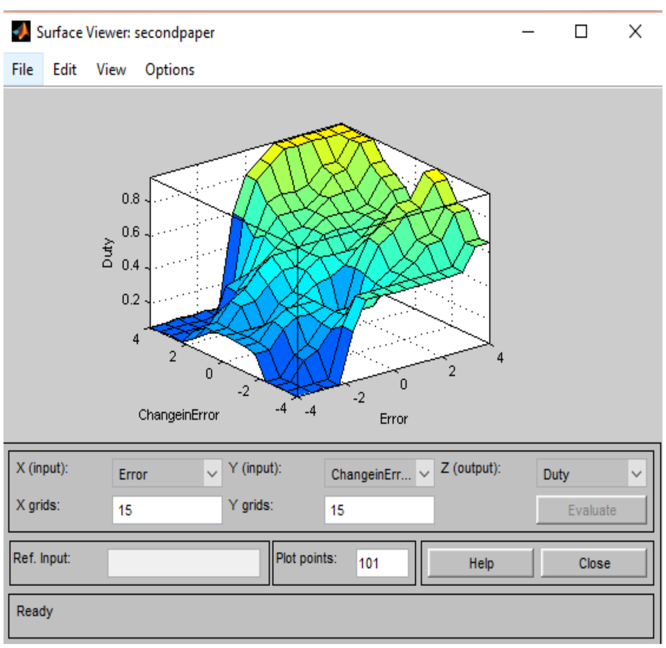

Figure 9: Surface view using fuzzy logic designer app (MATLAB)

IV. MATHEMATICAL ANALYSIS

In this section, mathematical analysis of the designed single-stage Ćuk converter will be presented operated by fuzzy logic controller. For instance, if at an instant of time 'error' is calculated to be -2.13V and the 'change in error' is evaluated to be 1.23V. So, rule 12 will be fired which states *"If error is negative medium and change in error is positive small then duty is large small"*. Inference system for the active rule has been shown in Figure 10. The duty cycle comes out to be 0.365 after carrying out the theoretical mathematical analysis.

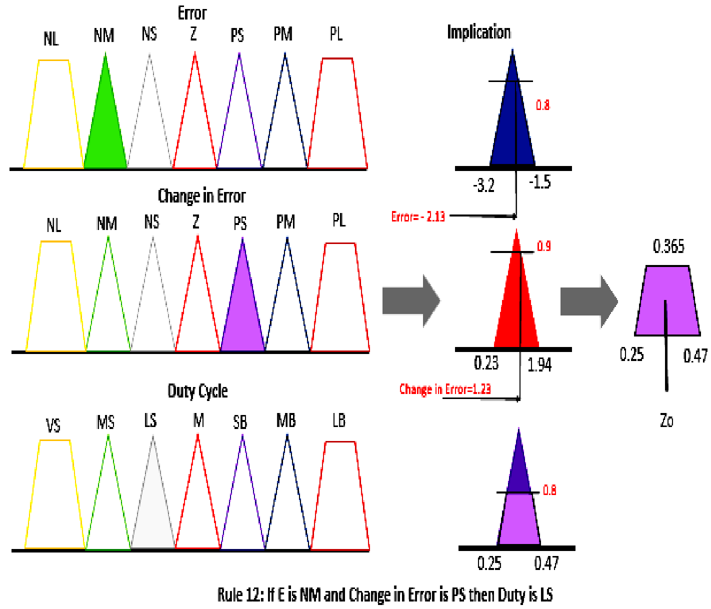

Figure 10: Mathematical analysis of fuzzy logic controller

The implication method utilized in Figure 10 is based upon Mamdani composition. Negative Medium membership function was selected for Error input and Positive Small membership function was selected for Change in Error input. The range of NM error is from -3.2 to -1.5. If error is -2.13, the degree of membership comes out to be 0.8. The range of PS change in error is from 0.23 to 1.94. If change in error is 1.23, the degree of membership comes out to be 0.9. When Mamdani based implication is used, the output fuzzy variable i.e., duty is clipped at minimum of {0.8, 0.9}. For Rule No: 12, the output membership function corresponds to Large Small and it is truncated at 0.8. In order to obtain crisp value, centroid method is used as illustrated in equations below.

$$Z_o = \frac{\sum_{i=1}^{n} Z_i \mu_{out}(Z_i)}{\sum_{i=1}^{n} \mu_{out}(Z_i)} \quad (3)$$

$$\sum_{i=1}^{n} Z_i \mu_{out}(Z_i) = (0.3 \times 0.4) + (0.32 \times 0.8) + (0.36 \times 0.8) + (0.42 \times 0.8) + (0.45 \times 0.4) \quad (4)$$

$$\sum_{i=1}^{n} \mu_{out}(Z_i) = 0.4 + 0.8 + 0.8 + 0.8 + 0.4 \quad (5)$$

$$Z_o = Duty\ Cycle = 0.365 \quad (6)$$

V. SIMULATIONS

In Figure 11, the complete system in MATLAB Simulink environment has been shown. A Ćuk converter has been interfaced with the fuzzy logic controller which was developed in the preceding section. The inputs to the controller can be evaluated using the reference voltage command and the output voltage. The output of fuzzy logic controller is the command for duty cycle which ranges from

0~1. This command is given as input to the PWM generator which drives the gate circuit of the converter.

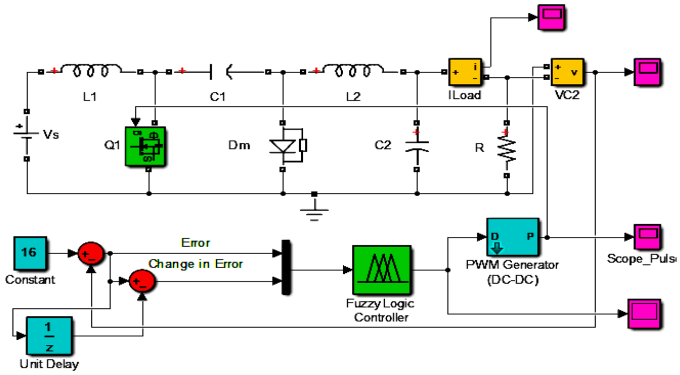

Figure 11: MATLAB simulink block diagram of Ćuk converter using fuzzy logic controller

When reference voltage was set greater than the input voltage, the converter operates in the boost mode as discussed in section II of this paper. When V_{input}=13V and $V_{reference}$=20V, the output voltage has been shown in Figure 12 and output current has been shown in Figure 13.

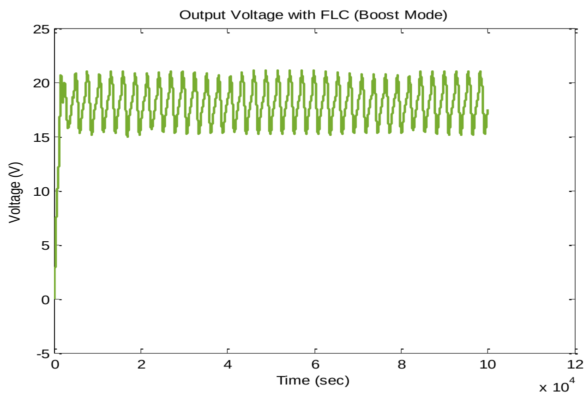

Figure 12: Output voltage with FLC in boost mode

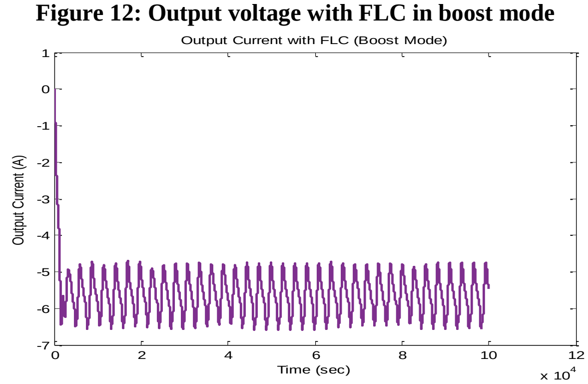

Figure 13: Output current with FLC in boost mode

When reference voltage was set lower than the input voltage, the converter operates in the buck mode. Suppose, when V_{input}=13V and $V_{reference}$=7V, the output voltage has been shown in Figure 14 and output current has been shown in Figure 15.

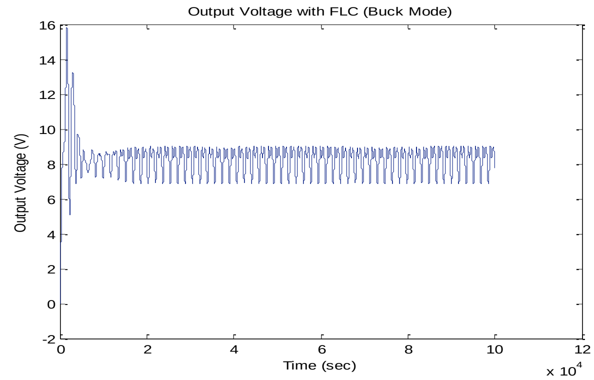

Figure 14: Output voltage with FLC in buck mode

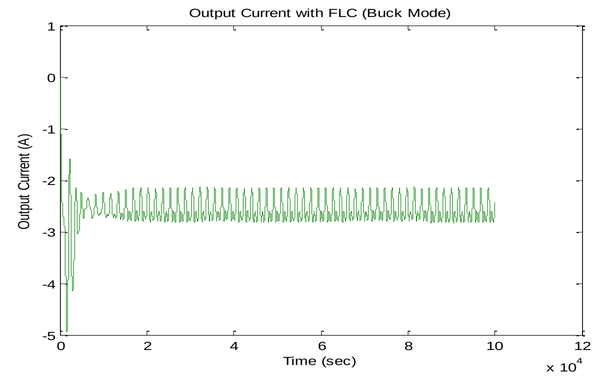

Figure 15: Output current with FLC in buck mode

In boost mode, the on-time of pulses is greater than the off-time as demonstrated in Figure 16 which shows the pulses generated by the fuzzy logic controller for a reference voltage greater than the input voltage. In Figure 17, the duty cycle is less than 0.5 as the converter operates in the buck mode.

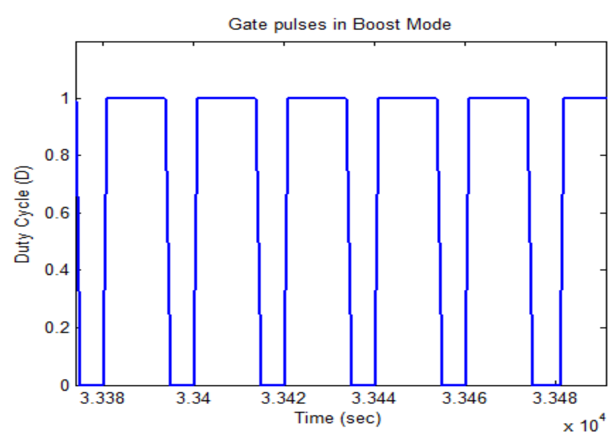

Figure 16: Gate pulses using FLC in boost mode

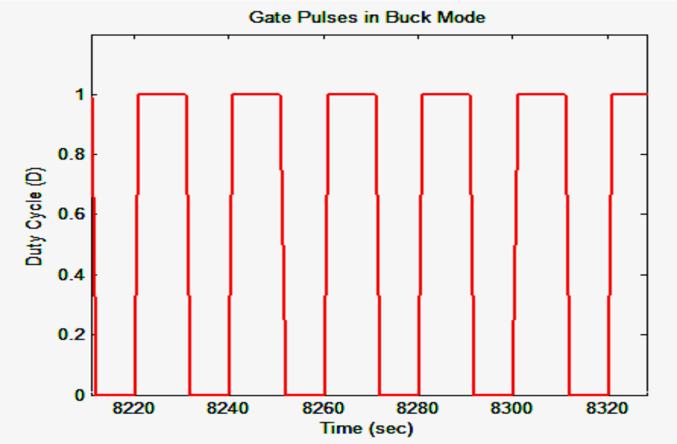

Figure 17: Gate pulses using FLC in buck mode

VI. RESULTS AND DISCUSSIONS

The duty cycle calculated for Rule No: 12 in section IV of this paper comes out to be 0.365 and MATLAB validates this value for the selected values of the error and change in error using the rule viewer window of the fuzzy logic designer app. The controller developed works effectively for the voltage regulation with an error of ~1V. The ripple present in output voltage and output current can be further reduced by modifying the value of the filter capacitor. For exact fine tuning of the system, the membership functions can be updated to reduce the error present in the output voltage. The paper already accommodated the overlapping of the membership functions essential for tuning of the system. Moreover, shapes and range of membership functions can also be changed to see the behavior of the system. The main aim of this paper was the regulation of DC bus voltage using an intelligent controller so that when the DC micro-grid is interfaced with the main grid, then circulating currents will not flow due to difference in voltage. In Section II of the paper, waveforms have been plotted using the inverted output voltage of the Ćuk converter. In Section V simulations have been done for fuzzy logic controller by considering the positive output voltage of the Ćuk converter for sake of convenience and exact computation of error and change in error inputs.

VII. CONCLUSION

In this paper a single-stage based Ćuk converter has been designed. The converter worked accurately in buck and boost modes for the given duty cycles using PWM technique. Then the converter was operated in a closed loop mode where an intelligent controller was utilized in a feedback path. The inputs to the intelligent controller were error and change in error. The error was computed using the reference voltage and the current output state whereas its derivative dictates the rate of change of error. After having these inputs, the fuzzy logic controller searches in the look up table/rule matrix for the active rules and computes the output fuzzy variable according to specific implication and defuzzification method. In this paper, Mamdani method was utilized as the implication method and for defuzzification, centroid of area method was employed. Moreover, mathematical analysis was also presented for one of the fired rules. The results were successfully validated using Simulink block of MATLAB along with Fuzzy Logic Controller App. As far as the future scope of the proposed system is concerned, the fuzzy logic controller developed can be integrated with maximum power point tracking algorithm for DC-DC Ćuk converter in order to serve as a potential candidate for real time smart grid applications under variable load conditions and weather fluctuations.

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