DESIGN OF NON-LINEAR CONTROLLED ZCS – QR BUCK CONVERTER USING GSSA

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ABSTRACT

A Fuzzy controlled DC-DC buck converters which maintains the load for various load and line conditions is presented in this paper. Processors exhibit variation in load current dynamically from few mA to Amps during operation. In this paper efficiency optimization is carried out for light and heavy load scenarios for variations in supply by varying the duty cycle of switching device. The primary design objective is to maintain the load due to dynamic changes in load. A Fuzzy logic approach for DC-DC buck converter is applied to validate the proposed methods in a Zero Current Switching (ZCS) Quasi Resonant (QR) Buck Converter which is operated in Half – wave (HW) mode at higher frequencies to substantially reduce switching loss and hence attain higher efficiency and power density. Analysis is done in four modes using an unified Generalized State Space Averaging (GSSA) technique to obtain its mathematical model and this technique focus mainly on the low frequency behaviour of the circuit, giving a low order representation.

KEYWORDS: *GSSA, Non-Linear control, Quasi Resonant converter*

I. INTRODUCTION

The switched mode DC - DC converters are the most widely used power electronics circuits for its high conversion efficiency and flexible output voltage. These converters are designed to regulate the output voltage against the changes of the input voltage and load current. This leads to the requirement of more advanced control methods to meet the real demand [1]. Many control methods are developed for the control of dc-dc converters. To obtain a control method that has the best performances under any conditions is always in demand. Conventional dc-dc converters have been controlled by linear voltage mode and current mode control methods. These controllers offer advantages such as fixed switching frequencies and zero steady-state error and give a better small-signal performance at the designed operating point. But under large parameter and load variation, their performance degrades [2], [3].

The complexity of the system and increasingly demanding closed loop system performance necessitates the use of more sophisticated controllers and in particular, research has been directed at applying non linear control principles to the regulation and dynamic control of output voltage of the converter. With the aid of advanced microcomputer technology, digital control of power converter becomes feasible but such methods involve a lot of complex equations and calculations. If the control method is based on an artificial intelligence instead of solving equations arithmetically, the required processing time of the controller can be reduced [4].

In Zero Current Switching, the resonant switch works on the zero current state during switching ON and OFF moment in order to offer many distinct advantages such as self – commutation, low switching stress and loss, reduced electromagnetic interference and noise, and faster transient response to load and line variations [5]. In addition, the voltage waveform of the switching is shaped into a smooth, quasi sinusoidal wave in one time period. The Half wave mode Zero Current Switched Quasi Resonant converter [6] implemented here for power conversion use only uni directional switch and hence it is not able to return excessive tank energy to the source. Consequently, its conversion frequency has to be varied over the wide range to maintain the voltage regulation for a variable load [7].

State Space Averaging [8], [9] is the most widely used method to the modeling and analysis of both the AC and DC behaviour of conventional Pulse Width Modulated switching converters in a systematic manner. However, it cannot be applied to Quasi or Sub Resonant converters [10] as the physical principles are not clear and the mathematical analysis is lacking. Therefore, a unified generalized State Space Averaging Technique is proposed to overcome the limitations of conventional State Space Averaging method and to model and analyze such converters with accuracy.

Design of fuzzy logic controller [11] is easier than other advanced control methods in that its control function is described by using fuzzy sets and IF – THEN rules rather than cumbersome mathematical equations or large look up – tables; it will greatly reduce the development cost and time and needs less data storage in the form of membership functions and rules in order to simplify the complexity of design. It can also exhibit increased robustness in the face of changing circuit parameters, saturation effects, and external disturbances and so on. Therefore, the focus here is strictly on the feasibility of implementing a fuzzy logic based controller to improve the system's performance.

In this paper Section II covers about the Generalized State Space Averaging (GSSA) technique, Section III and IV describes the modeling and analysis of Quasi-Resonant (QR) Buck Converter, Section V describes the Fuzzy implementation for control of QR Buck Converter and Section VI describes the Design parameters considered for QR Buck Converter, while Section VII describes the Simulation part carried out with Matlab Simulink® version R2010a, Section VIII discusses the results obtained from simulation of Fuzzy controlled QR Buck Converter with GSSA and Section IX enumerates the performance of Fuzzy Controlled QR Buck Converter with GSSA.

II. GENERALIZED STATE-SPACE AVERAGING TECHNIQUE

Consider a periodically switched network with k different switched modes in each switching cycle, described by the state equation

$$X(t) = A_i\, x(t) + B_i(t), \quad i = 1, 2\ldots k \tag{1.0}$$

The equation (1.0) can be characterized by the following Generalized State Space Averaging [9], [10] equation as

$$x = \{\sum_{i=1}^{k} d_i A_i\}x + 1/T \sum_{i=1}^{k} \int_{ti-1}^{ti} B_i(\lambda)d\lambda \tag{1.1}$$

T is the switching period,

$f_{s} = 1/T$ is the switching frequency and

$f_{o} =$ the highest natural frequency of state matrix A_i.

If the input control variable functions Bi are bounded and

f_s is much greater than f_o, then, the equation (1.1) can be obtained.

III. MODELING OF QUASI-RESONANT BUCK CONVERTER

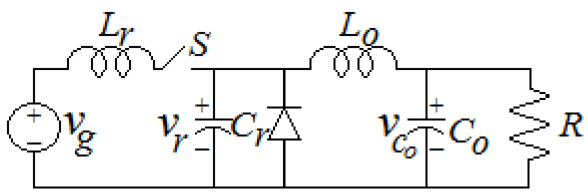


Fig 1 ZCS – QRC Buck Converter

It is known that in this converter two fundamentally different kinds of energy storage states are present. The state variables in the resonant tank can be determined in each mode of operation once the state variables associated with the low pass filter are determined and it reach zero periodically in each cycle. Thus, for the modelling and analysis of Quasi Resonant Converter [5], [6] the key variables are the state variables of the filter state whereas the variables associated with the resonant tank are considered as input control variables.

IV. ANALYSIS OF QUASI-RESONANT BUCK CONVERTER

An analysis of quasi resonant step down Converter [7] can be performed by first analyzing the behavior of the state variables of the filter states using the Generalized State Space Averaging Technique [9] with the following assumptions.

1 The switching frequency is much higher than the natural frequency of the low pass filter and hence the state variables of the filter state can be regarded as constant in each cycle.

2. All the elements including the semiconductor switches are ideal which simplifies the generation of basic equations and relationships.

The reduced – order state equation of the proposed converter can be formulated by analyzing the circuit in its four modes of operation as follows.

The switch S is responsible for the power transferred to the load. L_r and C_r constitute series resonance circuit with its oscillation initiated by the turn ON of the switch S.

4.1 Inductor Charging Mode

The switch is turned ON at $t = t_0$ and current in L_r rises linearly and the diode D is on. Because of the current fly wheeling through the diode it appears as a short circuit and the entire input voltage appears across L_r. The reduced-order state equation of the ZCS-QRC buck converter [7], [8] in this stage is equation (4.1).

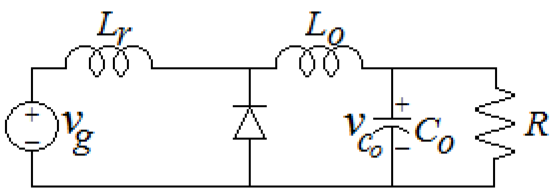


Fig 2 Inductor charging mode

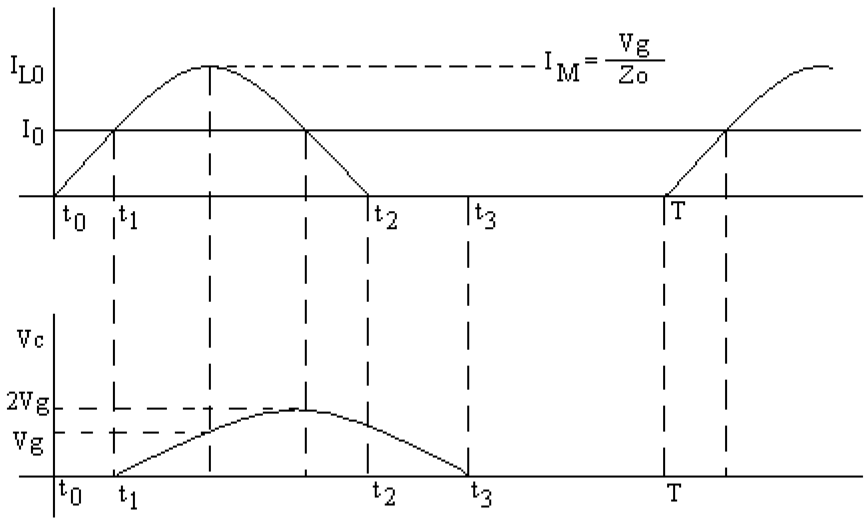


Fig 2.1 Waveform: Resonant Switch Converter: ZCS

$$\begin{bmatrix} \frac{dv_{c0}}{dt} \\ \frac{di_{L0}}{dt} \end{bmatrix} = \begin{bmatrix} \frac{-1}{RC_0} & \frac{1}{C_0} \\ \frac{-1}{L_O} & 0 \end{bmatrix} \begin{bmatrix} v_{co} \\ i_{L0} \end{bmatrix} \quad (4.1)$$

and the duration of this operation mode, τ_1 (t_1-t_0) is

$$\tau_1 = \frac{L_r i_{Lo}}{v_g} \quad (4.2)$$

4.2 Resonant Mode

Both the inductor current and the capacitor voltage vary sinusoidally with the resonant frequency until t_2. The current eventually drops to zero at t_2 and the switch is turned OFF resulting in zero current switching. The reduced-order state equation of the ZCS-QRC buck converter [7] in this stage is equation (4.3)

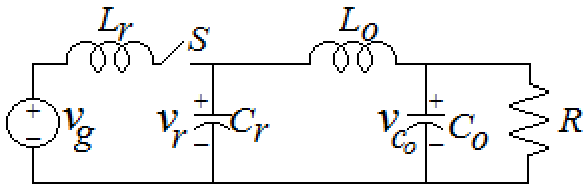


Fig 3 Resonant mode

$$\begin{bmatrix} \frac{dv_{c0}}{dt} \\ \frac{di_{L0}}{dt} \end{bmatrix} = \begin{bmatrix} \frac{-1}{RC_0} & \frac{1}{C_0} \\ \frac{-1}{L_0} & 0 \end{bmatrix} \begin{bmatrix} v_{co} \\ i_{L0} \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{V_{Cr}}{L_0} \end{bmatrix} \quad (4.3)$$

and the duration of this operation mode, τ_2 (t_2-t_1) is

$$\tau_2 = \frac{\alpha_i}{\omega} \quad (4.4)$$

Where $\alpha_i = \sin^{-1}(\frac{-Z_n i_{Lo}}{v_g})$

$\omega = 2\pi f_n = \frac{1}{2\pi\sqrt{L_r C_r}}$ is the resonant angular

Frequency in rad/s

$$Z_n = \sqrt{\frac{L_r}{C_r}}$$

Z_n is the characteristic or normalized impedance in ohms and

$$V_{cr}(t) = V_g(1-\cos \omega t) \quad (4.5)$$

4.3 Capacitor Charging Mode

Beyond t_2, the positive capacitor voltage keeps the diode reverse biased and the capacitor discharges into the load. The capacitor voltage linearly decreases and drops to zero at t_3. The reduced-order state equation of the ZCS-QRC buck converter [8] in this stage is equation (4.6).

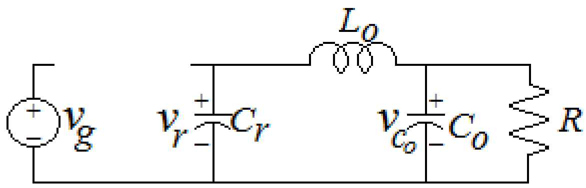


Fig 4 Capacitor Discharging Mode

$$\begin{bmatrix} \frac{dv_{c0}}{dt} \\ \frac{di_{L0}}{dt} \end{bmatrix} = \begin{bmatrix} \frac{-1}{RC_0} & \frac{1}{C_0} \\ \frac{1}{L_0} & 0 \end{bmatrix} \begin{bmatrix} v_{c0} \\ i_{L0} \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{v_{Cr}}{L_0} \end{bmatrix} \tag{4.6}$$

and the duration of this operation mode τ_3 (t_3-t_2) is

$$\tau_3 = \frac{C_r v_g (1-\cos\alpha_i)}{i_{Lo}} \tag{4.7}$$

and $$V_{cr}(t) = -\frac{iL_o}{C_r} t + V_g (1 - \cos \propto_i) \tag{4.8}$$

4.4 Free Wheeling Mode

The reduced-order state equation of the ZCS-QRC buck converter in this stage is equation (4.9).

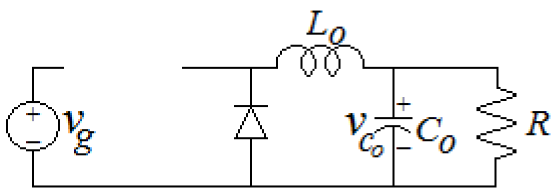


Fig 5 Free Wheeling Mode

$$\begin{bmatrix} \frac{dv_{c0}}{dt} \\ \frac{di_{L0}}{dt} \end{bmatrix} = \begin{bmatrix} \frac{-1}{RC_0} & \frac{1}{C_0} \\ \frac{-1}{L_O} & 0 \end{bmatrix} \begin{bmatrix} v_{co} \\ i_{L0} \end{bmatrix} \tag{4.9}$$

and the duration of this operation mode is

$$\tau_4 = T - \tau_1 - \tau_2 - \tau_3 \tag{4.10}$$

Rewriting the equations namely (4.1), (4.3), (4.6), (4.9) in the same way as for (1.0) gives

$$A_1 = A_2 = A_3 = A_4 = \begin{bmatrix} \frac{-1}{RC_0} & \frac{1}{C_0} \\ \frac{-1}{L_O} & 0 \end{bmatrix}$$

$$B_1 = B_4 = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \text{ and } B_2 = B_3 = \begin{bmatrix} 0 \\ \frac{v_{Cr}}{L_0} \end{bmatrix} \tag{4.11}$$

The natural frequency of the resulting reduced order state equation (4.11) is the corner frequency of the low-pass filter, which is much lower than the switching frequency. The GSSA technique can be now applied to the modelling of (4.11) and can be obtained as

$$\begin{bmatrix} \frac{dv_{c0}}{dt} \\ \frac{di_{L0}}{dt} \end{bmatrix} = \begin{bmatrix} \frac{-1}{RC_0} & \frac{1}{C_0} \\ \frac{1}{L_0} & 0 \end{bmatrix} \begin{bmatrix} v_{c0} \\ i_{L0} \end{bmatrix} + \frac{v_g}{L_o} \cdot \frac{f_s}{2\pi f_n} . H_i(v_g, i_{L0}) \quad (4.12)$$

$$H_i(v_g, i_{L0}) = \frac{z_n i_{L_o}}{2v_g} + \propto_i + \frac{v_g}{z_n i_{L_o}} (1 - \cos \propto_i) \quad (4.13)$$

The GSSA [8], [9] equation (4.12) and (4.13) of the Zero Current Switching Quasi Resonant Buck converter is valid not only for characterizing its steady state but also characterizing its transient behavior.
To perform its small signal characteristic analysis, perturbation is introduced to the variables namely v_g, i_{Lo}, v_{c0}, f_s and neglecting all second and higher order terms of small-signal perturbations, the ac small-signal state equation is obtained.
Using the Laplace transformation to the ac small signal state equation the transfer function of the buck converter is obtained.

$$\frac{v_o}{v_g} = \frac{M\left(1 - \frac{J_i}{H_i}\right)}{s^2 L_o C_o + s\left(\frac{L_o}{R} - RC_o \frac{J_i}{H_i}\right) + 1 - \frac{J_i}{H_i}} \quad (4.14)$$

V. FUZZY CONTROLLER FOR QUASI-RESONANT BUCK CONVERTER

The control action is determined from the evaluation of a set of simple linguistic rules which require a thorough understanding of the process to be controlled. The general structure of a fuzzy logic control [12] is represented in Figure.6

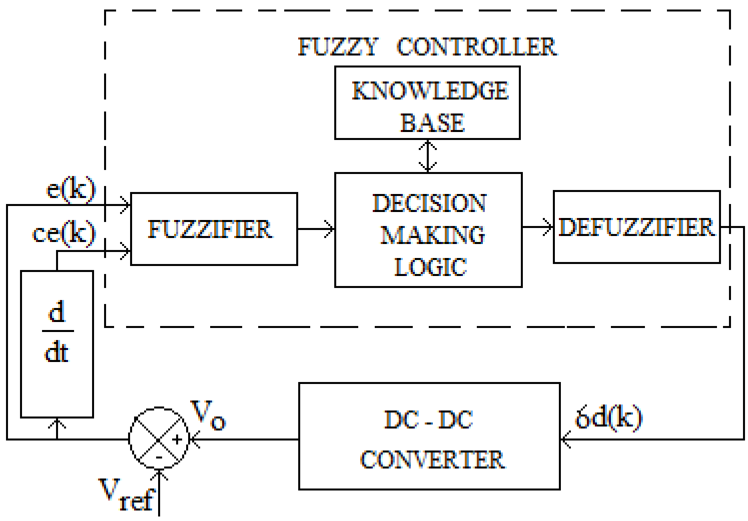


Fig 6 Fuzzy Logic Controller

5.1 Identification of Input and Output

Error, e(k) and Change in error voltage [13], ce(k) are the two inputs to the Fuzzy Controller and change in duty cycle is the resulting output of Fuzzy Controller. The error is computed by subtracting the actual output voltage, V_o from the desired or reference voltage, V_g and the derivative input, which

reflects the rate at which the error is changing, is calculated by subtracting the previous error from the current error and in mathematical form [14], ce(k)=e(k)- e(k-1) at the k^{th} sampling instant. The output of the fuzzy control algorithm is the change of duty cycle [δd(k)]. The duty cycle d(k), at the k^{th} sampling time, is determined by adding the previous duty cycle[d(k-1)] to the calculated change in duty cycle as d(k)=d(k-1)+ δd(k).
Depending upon the magnitude of error and change in error, the switching frequency of the switch S is varied for regulating the output voltage.

5.2 Membership Functions

Three Gaussian membership functions are chosen to model, analyze and simulate the Fuzzy Controller [13], [14]. The membership function for each fuzzy variable has been defined taking into account the conditions of normality and convexity of fuzzy sets; the membership function embodies the mathematical representation of membership in a set and are required to have uniform shapes, parameters and functions for the sake of computational efficiency, efficient use of the computer memory and performance analysis. It also gives the degree of confidence about the result. The membership functions for the input and output are shown in Fig 7, 8 and 9 and it characterizes the fuzziness; whether the elements in the set are discrete or continuous.

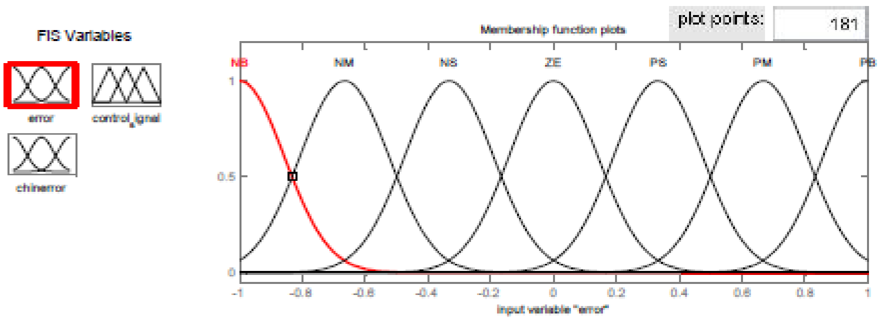


Fig 7 Membership function for error signal

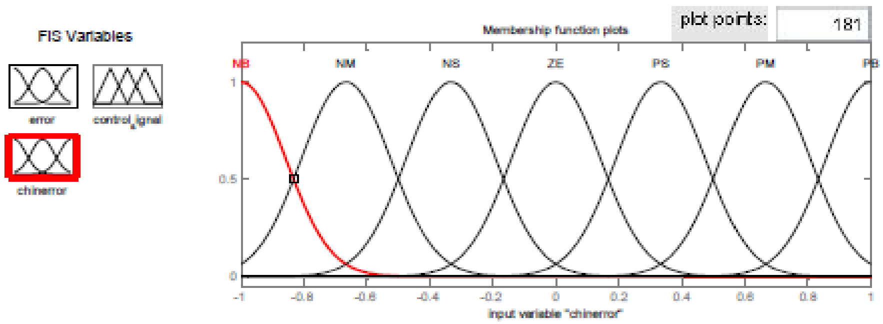


Fig 8 Membership function for change in error signal

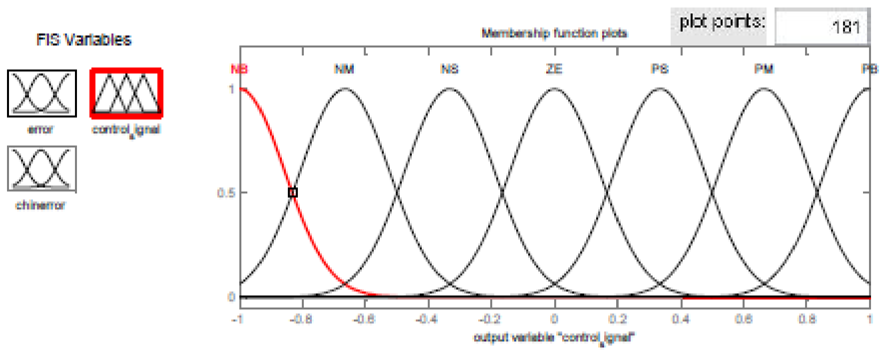


Fig 9 Membership function for control signal

5.3 Fuzzification

Fuzzy sets contain objects that satisfy imprecise properties of membership. It provides a mathematical way to represent vagueness in humanistic systems and must be defined for each input and output variables. For ease of computation, seven fuzzy subsets are defined by the library of fuzzy set values for the error, e and change in error, ce and they are NB (Negative Big), NM (Negative Medium), NS (Negative Small), ZE (Zero), PS (Positive Small), PM (Positive Medium), and PB (Positive Big).

5.4 Development of Rule Base

Normally, the fuzzy rules [4], [12]-[20] are heuristic in nature; they are typically written as antecedent – consequent pairs of IF THEN structure and the inputs are combined by AND operator. The antecedent and consequent are the description of process state and control output respectively in terms of a logical combination of fuzzy propositions. 49 rules are formed depending on the number of membership functions in order to play a key role in the improvement of system performance.

1. If the output of the converter is far from the set point, the change of the duty cycle must be large so as to bring the output to the output to the set point quickly.
2. If the output of the converter is approaching the set point, a small change of the duty cycle is necessary.
3. If the output if the converter is near the set point and is approaching it rapidly, the duty cycle must be kept constant so as to prevent overshoot.
4. If the set point is reached and the output is still changing, the duty cycle must be changed slightly to prevent the output from moving away.
5. If the set point is reached and the output is steady, the duty cycle remains unchanged.
6. If the output is above the set point, the sign of change of duty cycle must be negative and vice-versa.

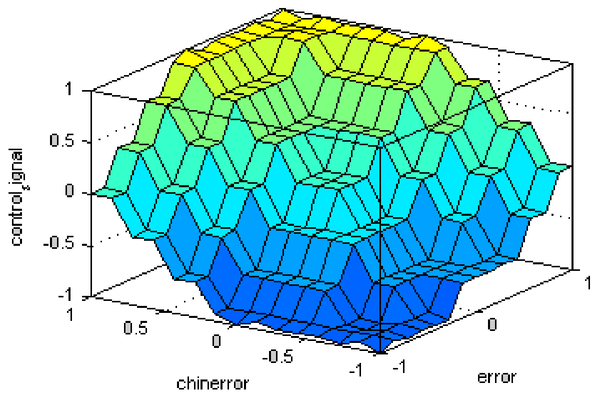


Fig 10 Rule base in terms of surface view

Table 1: Rules for Control Signal

e \ ce	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NB	NM	NM	NS	ZE	PS
NS	NB	NM	NS	NS	ZE	PS	PM
ZE	NM	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PS	PM	PB
PM	NS	ZE	PS	PM	PM	PB	PB
PB	ZE	PS	PM	PB	PB	PB	PB

5.5 De-Fuzzification

Conservation of the fuzzy to crisp or non-fuzzy output is defined as defuzzification. Mean of Maxima (MOM) method is implemented, where only the highest membership function component in the output is considered.

VI. DESIGN DATA

The Fuzzy controlled Quasi Resonant buck converter [15]-[20] depicted in Fig.11 is designed as per the specification mentioned in the Table 2 and it is used in hardware circuits of computer.

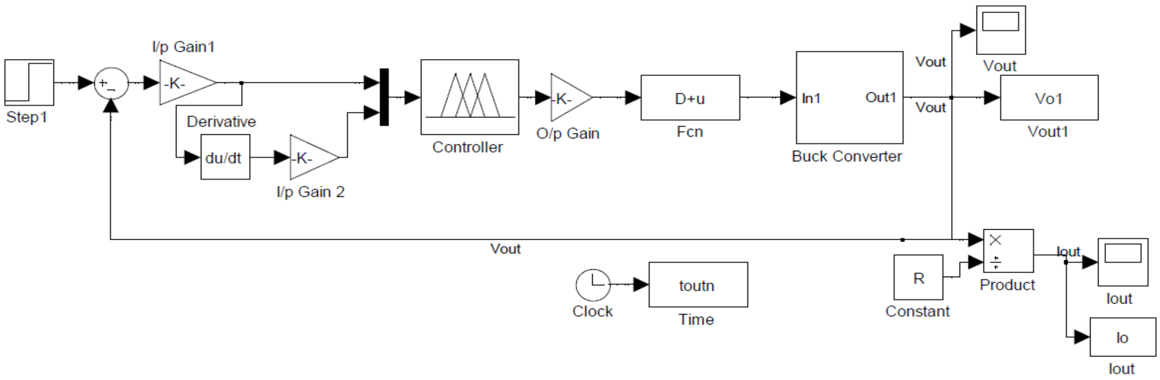


Fig 11 Fuzzy Controller for QRC Buck converter

Table 2: Design Parameters

No.	Parameter	Symbol	Value
1	Input Voltage	V_g	**4 – 20V**
2	Output Voltage	V_o	**3. 3V**
3	Resonant Inductor	L_r	**0. 2mH**
4	Resonant Capacitor	C_r	**20µF**
5	Filter Inductor	L_o	**0.2mH**
6	Filter Capacitor	C_o	**20 µF**
7	Load Resistance	R	**0. 25 – 1 Ω**
8	Switching Frequency	f_s	**200 Khz**
9	Time period	T	**5 µs**
10	Natural Frequency	f_o	**2.5165 kHz**
11	Resonant Frequency	f_r	**2. 5165 kHz**
12	Normalized impedance	Z_n	**3.1623 Ω**
13	Load Current	I_o	**3.3- 13.2Amps**
14	Output Power(max)	P_O	**174.24 W**

VII. SIMULATION

The Quasi Resonant Buck Converter as shown in Figure 11 is designed in Matlab Simulink® version R2010a with the parameters shown in Table 2 and the Fuzzy input and output parameters are set from -1 to +1 as shown in Figures 7, 8 and 9 with the rule base for the control signal as described by the Table 1 and the Figure 10. The duty cycle of the converter can be varied from -1 and 0 for the half wave configuration. The results of digital simulation for the value of duty cycle equal to -0.2 for various conditions of supply and load variations are shown hereunder in Table 4. It is shown that the proposed technique has much faster simulation speed than the numerical method and gives better performance of voltage regulation. To compare the transient performance of both the Buck Converter and Quasi-Resonant Buck Converter, five different cases spanning the entire operating range of the converter are selected as given in Table 3. The five different cases are;

1. Minimum line and maximum load condition
2. Minimum line and light load condition
3. Mid range line and load condition
4. Maximum line and maximum load condition
5. Maximum line and light load condition

TABLE 3: Output Voltage of the Resonant Buck Converter

Case	Input Voltage (Volts)	Load Resistor (Ohms)	Load Current (Amps)	Output Voltage (Volts)
1	4	0.25	13.2	3.3
2	4	1	3.3	3.3
3	10	0.5	6.6	3.3
4	20	0.25	13.2	3.3
5	20	1	3.3	3.3

The value of settling time for various conditions of supply and load variations is shown hereunder in Table 4.

TABLE 4: Settling Time (ms) of the Converter

Case / J/H	1	2	3	4	5
0.0	1.349	20.362	6.485	1.340	21.593
-0.2	0.491	1.311	0.507	0.491	1.282
-0.4	0.198	2.230	0.879	0.196	2.230
-0.6	0.262	2.931	4.127	0.262	2.931
-0.8	0.304	3.479	1.403	0.375	3.479
-1.0	0.398	3.911	1.577	0.405	3.911

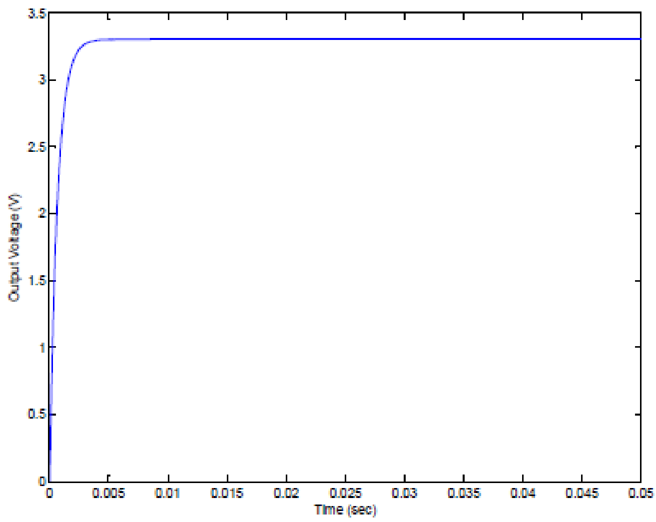
The settling time of the converter is found to be in the order of few milli seconds and this illustrate the stability of the system under various J/H parameters against varying load conditions as shown in Table 3 and 4. The following section shows the output waveform of the simulation for the load voltage and load current for J/H=-0.2 under varying load condition.

VIII. SIMULATION RESULTS

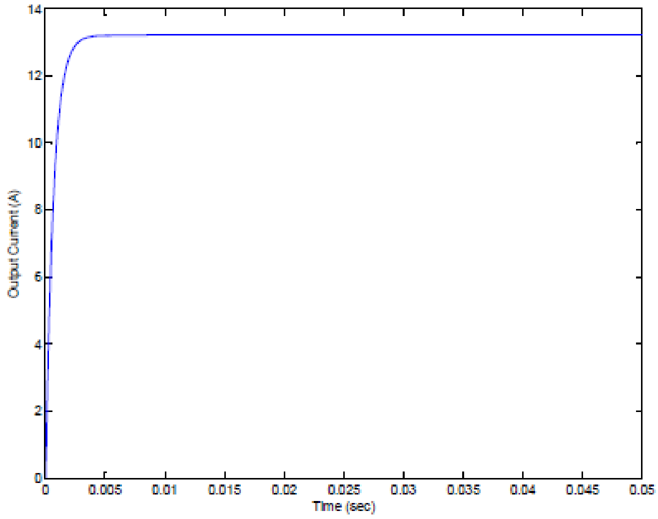
The simulation of Fuzzy controlled Quasi Resonant Buck Converter modeled with Generalized State Space Averaging technique is developed with Matlab Simulink® model of Version R2010a and the simulation is carried out for varying load conditions for various J/H parameters and the simulation results of V_{out} and I_{out} for J/H value -0.2 is shown in the following Figure 12.

J/H= -0.2

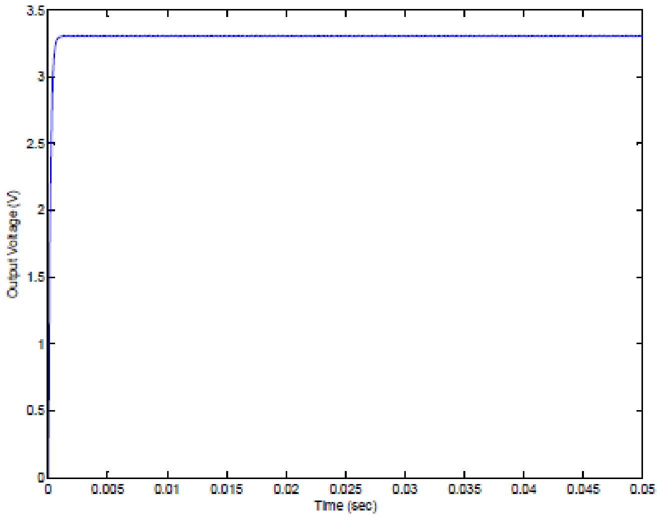
Case 1: V_{out}



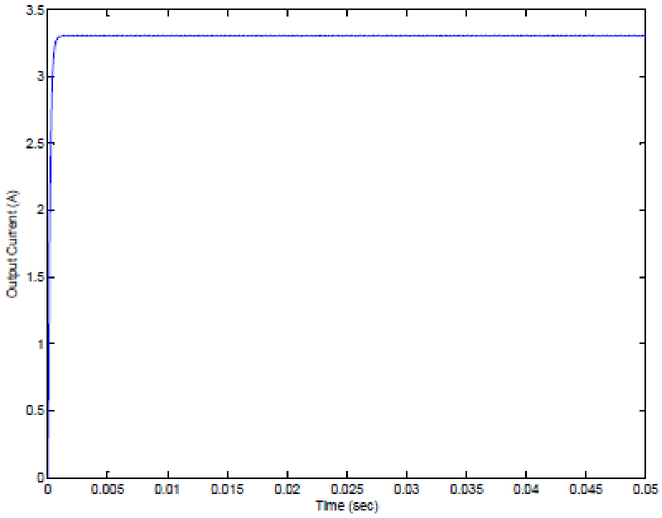
Case 1: I_{out}



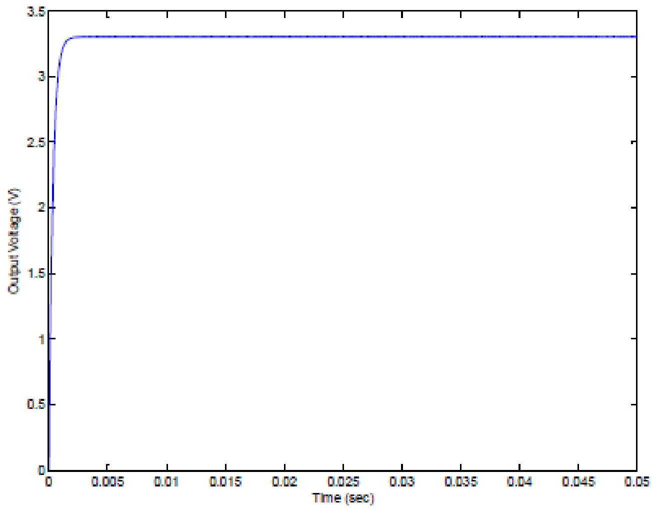
Case 2: V_{out}



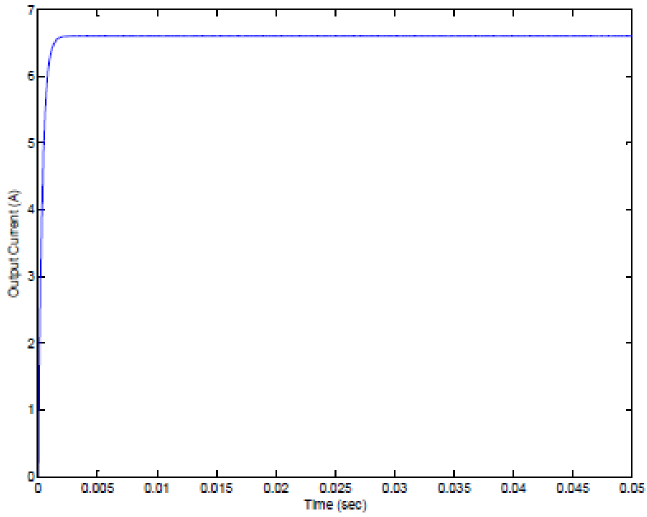
Case 2: I_{out}



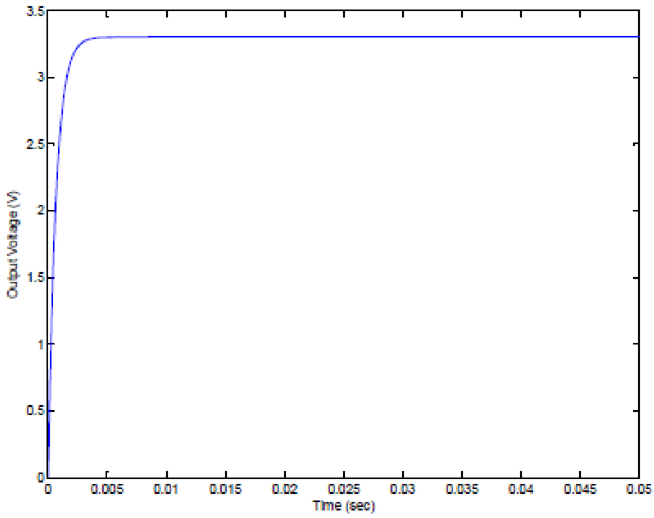
Case 3: V_{out}



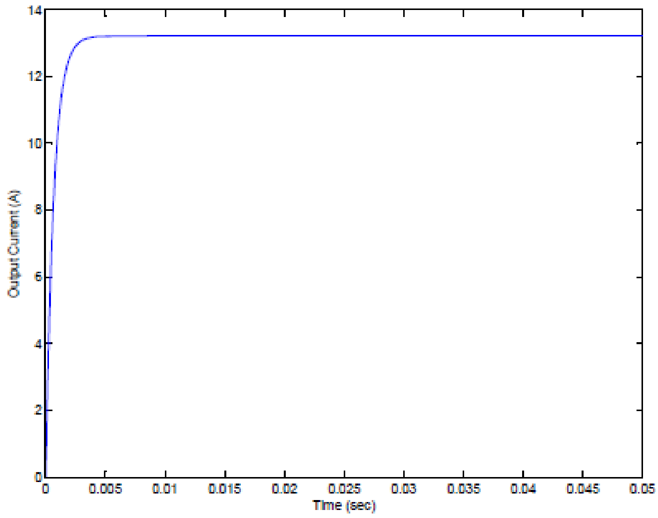
Case 3: I_{out}



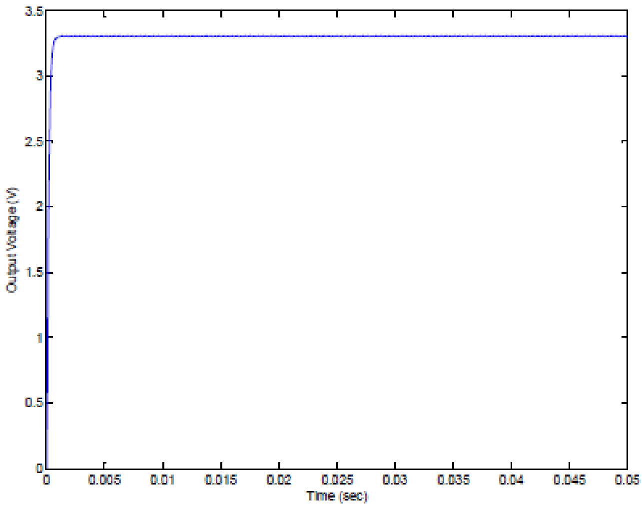
Case 4: V_{out}



Case 4: I_{out}



Case 5: V_{out}



Case 5: I_{out}

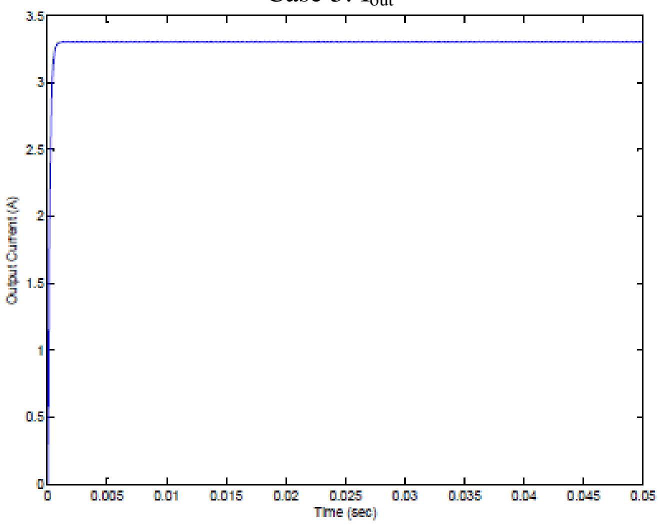


Fig 12 Simulation Results of V_{out} and I_{out} for J/H parameter from -0.2

IX. CONCLUSION

The Fuzzy controlled converter is reliable and efficient and the output voltage regulation of such converter against load and supply voltage fluctuations is validated by Matlab Simulink® model of QR Buck converter. It is verified by simulation that due to quasi resonance there is a drastic change in maximum overshoot and settling time in the output and the developed fuzzy control scheme has good rejection ability for line and load disturbances. The results thus obtained by simulation not only validate the system's operation but also permits optimization of the system's performance by iteration of its parameters.

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