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DESIGN AND SIMULATION OF FUZZY CONTROLLED QUASI RESONANT BUCK CONVERTER

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ABSTRACT

A controller based on Fuzzy logic is implemented and its application to the regulation of power converter is investigated. Being free of complex equations and heavy computation, it achieves fast dynamic response and adapts to varying conditions of operation. The topology is modeled using MATLAB software and operated at finite higher switching frequency to evaluate its closed-loop performance in respect of line and load regulation. It is verified by transient characteristics that due to quasi-resonance there is a drastic change in peak overshoot and settling time and the proposed strategy has good rejection ability for supply and load disturbances.

Keywords: Quasi Resonant Buck Converter, GSSA, Fuzzy logic, Line regulation and Load regulation.

1. INTRODUCTION

Power-electronic converter is the need of the day, may it be process control automation, telecommunication, energy conservation or medical instrumentation and it is imperative to design such converters capable of operating at higher frequency for achieving high power density [2]. The converter must be made increasingly reliable and the output voltage regulation of such converter against load and supply voltage fluctuations is an important criterion in design [18].

Crucial to the performance of power converters is the choice of control methods. Frequency domain analog methods predominantly used are based on an equivalent linear small signal model of the converter and this model has restricted validity especially for systems with strong non-linearity. It also cannot meet the more stringent requirement of today's digital circuit because of inherent disadvantages such as low flexibility, low reliability, temperature drift of the components and susceptibility to electromagnetic interference. The complexity of the system with non-linearity, the practical converter operation because of problems associated with parasitic resistance, stray capacitance and leakage inductance of the components, and increasingly demanding closed loop system performance necessitates the use of more sophisticated controllers. 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 [9]. 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 and the sluggish response shall be improved.

Among the various techniques of artificial intelligence, the most popular method to characterize and control a system that have vagueness, uncertainty is the Fuzzy logic and It was first propounded in the early 1970. Fuzzy logic is a departure from classical Boolean or crisp logic as it relies on human capability to understand system's behaviour and is based on qualitative control rules and quantitative mathematical theory [13]. It is one of the intelligent schemes that convert the linguistic control strategy based on expert knowledge into an automatic strategy or otherwise it implements non-numeric linguistic variables on a continuous range of truth values which allows intermediate values to be defined between conventional binary system [13], [4]. In addition, it has emerged as one of the most active and promising control methods in the power electronic systems such as speed control of AC and DC drives, feedback control of converters, non–linearity compensation, on and off line diagnostics, etc., due to its capability of fast computation with high precision. Therefore, it is a paradigm for the alternative design methodology which naturally provides the ability to deal with the highly non–linear, time–variant, complex and ill–defined systems where the mathematical models are difficult to be obtained or control variables are too hard to measure or where human reasoning, perception or decision making are inextricably involved or where the inputs are imprecise in nature [3].

Design of fuzzy logic or rule based non-linear controller is easier since its control function is described by using fuzzy sets and if–then predefined 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. It is adaptive in nature and can also exhibit increased reliability, robustness in the face of changing circuit parameters, saturation effects, and external disturbances and so on [15]. The focus is strictly on the feasibility of implementing a Fuzzy logic based controller to establish its superior performance on Quasi-Resonant Buck Converter over the Buck converter at various operating points of the converter. Simulation results for line and load regulation are depicted and peak overshoot and settling time are used to measure the system performance [10].

2. GENERALIZED STATE-SPACE AVERAGING TECHNIQUE

The state equation of a periodically switched network is

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

The equation (1.0) for the conventional method is characterized by the Generalized State Space Averaging equation [19] as

$$x = \{\sum_{i=1}^{k} d_iA_i\}x+1/T\sum_{i=1}^{k}\int_{t_{i-1}}^{t_i} B_i(\gimel)d) \qquad \gimel 1.1)$$

T is the switching period,

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

$f_{o=}$ the highest natural frequency of state matrix $A_{i.}$, and

B_i = bounded input control variable of the function.

3. SMALL SIGNAL MODEL OF THE CONVERTER

The Half-wave mode Zero Current Switched Quasi Resonant step down converter in Figure-1 operated in discontinuous conduction mode use only uni-directional switch [6] and it offers many distinct advantages such as self-commutation, low switching stress and loss, high efficiency and power density, reduced electromagnetic interference and noise, and faster transient response to load and line variations [22]. The first step is to obtain the most important small signal characteristic namely input-to-output or line-to-output voltage transfer function [8], also called as the open loop dynamic line regulation [11].

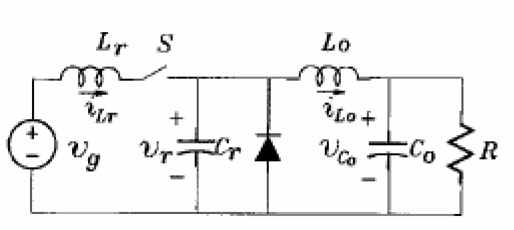


Figure-1. ZCS-QRC buck converter.

The transfer function of such converter under the worst case condition namely the minimum line and maximum load condition is the base in the design of the controller. The transfer function of such second order dynamic system is obtained as in (2.0) by analyzing the circuit in its four modes of operation as shown in Figures, 2, 3, 4 and 5 and Table-1 using the Generalized State Space Averaging Technique and it has overcome the limitations of the conventional method [12]. The small signal characteristic analysis is performed by introducing perturbation to the variables where capital letters stand for DC steady state components and the letters with hat symbol stand for the small signal perturbations [1].

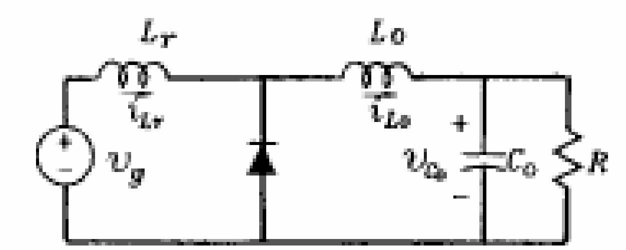


Figure-2. Inductor charging mode.

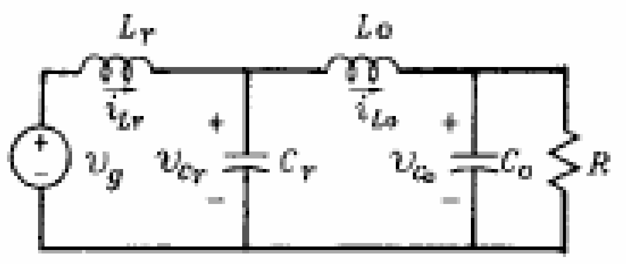


Figure-3. Resonant mode.

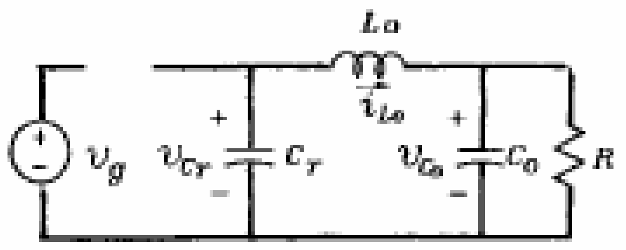


Figure-4. Capacitor discharging mode.

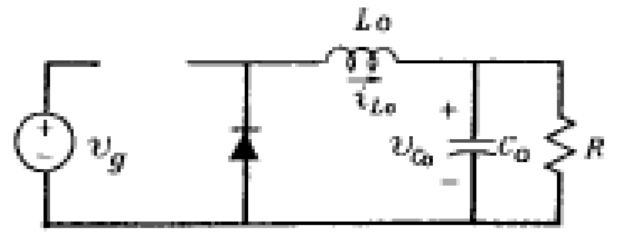


Figure-5. Free wheeling mode.

Table-1. Definition of the state.

No.	Mode	State of the Switch	State of the Diode
1	Inductor charging	CLOSED	ON
2	Resonant	CLOSED	OFF
3	Capacitor discharging	OPEN	OFF
4	Free wheeling	OPEN	ON

$$\frac{v_0}{v_g} = \frac{M\left(1 - \frac{J_i}{H_i}\right)}{s^2 L_0 C_0 + s\left(\frac{L_0}{R} - RC_0 \frac{J_i}{H_i}\right) + 1 - \frac{J_i}{H_i}} \qquad (2.0)$$

Where V_O = Output voltage, V_g = Input voltage, Lo = Filter inductor, Co = Filter (output) capacitor, R = Load resistor and,

$$M = \frac{V_0}{V_g} = \frac{F_s}{2\pi F_n} H_i(V_g, I_{L_o}) \qquad (2.1)$$

$$J_i(v_g, i_{L_o}) = \frac{Z_n i_{L_o}}{2v_g} - \frac{v_g}{Z_n i_{L_o}}(1 - \cos\alpha_i) \qquad (2.2)$$

$$H_i(v_g, i_{L_o}) = \frac{Z_n i_{L_o}}{2v_g} + \alpha_i + \frac{v_g}{Z_n i_{L_o}}(1 - \cos\alpha_i) \qquad (2.3)$$

$$Z_n = \sqrt{\frac{L_r}{C_r}} \qquad (2.4)$$

$$\alpha_i = \sin^{-1}\left(-\frac{Z_n i_{L_o}}{v_g}\right) \qquad (2.5)$$

4. FUZZY CONTROLLER FOR QUASI RESONANT BUCK CONVERTER

A process control algorithm that is based on fuzzy logic is called Fuzzy control and it essentially embeds the intuition and experience of a human operator [17]. The general structure of a fuzzy controller is represented in Figure.6 and the algorithm consists of a set of fuzzy rules which are related by the concepts of fuzzy implication and the compositional rule of inference [5].Its perfomance depends on rules size and tuning parameters [16]. The steps involved in the design in off-line implementation are:

i. To select control elements and parameters as scaling factors for input and output signals.
ii. To partition the universe of discourse of the interval spanned by each variable into a number of fuzzy subsets, assigning each a linguistic label.
iii. To assign membership function for each fuzzy subset.
iv. To assign the fuzzy relational between the input and output fuzzy subsets, thus forming the rule base.
v. To choose appropriate scaling factors for the input and output variables in order to normalize the variables to [-1, 1] or [0,1] interval.
vi. To fuzzify the inputs or to classify the input data into suitable linguistic values or sets to the controller.
vii. To use fuzzy appropriate reasoning to infer the output contributed from each rule.
viii. To aggregate the fuzzy outputs recommended by each rule
ix. To apply defuzzification technique to form a crisp output.
x. To send the change of control action to control the plant.

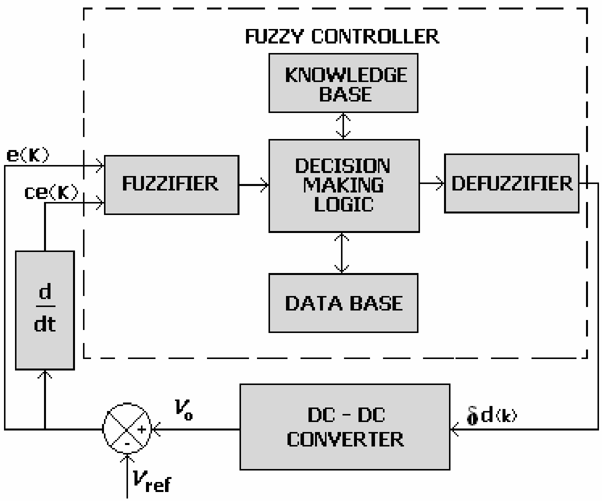


Figure-6. Basic configuration of closed loop fuzzy controller.

Off-line implementation thus employs a look up table built according to the setoff all possible combinations of input variables and can actually reduce the controller actuation time as the only effort is limited to consulting the table at each iteration.

(a) **Identification of inputs and output**

The inputs to the fuzzy controller are the error e (k) and the change in error voltage Ce (k) which are defined as

E (k) = $V_0 - V_{ref}$
Ce (k) = e (k) – e (k-1)

Where Vo is the sampled output voltage of the DC-DC converter, Vref is the reference output voltage and the symbol k denotes value at the beginning of the kth switching cycle. The output of the fuzzy controller is the change in duty cycle and is defined as
D (k) = d (k-1) + η.δd (k)

Where δd (k) is the inferred change in duty cycle by the fuzzy controller at the k^{th} sampling time and η is the gain factor of the fuzzy controller [7].

(b) **Membership functions**

Three continuous Gaussian membership functions are chosen to model, analyze and simulate the Fuzzy Controller. It has been defined taking into account the conditions of normality and convexity of fuzzy sets; it embodies the mathematical representation of membership in a set and is required to have uniform shapes, parameters and functions for the sake of computational efficiency, efficient use of the computer memory and performance analysis. The membership functions for the input and output are shown in Figures 7, 8 and 9.

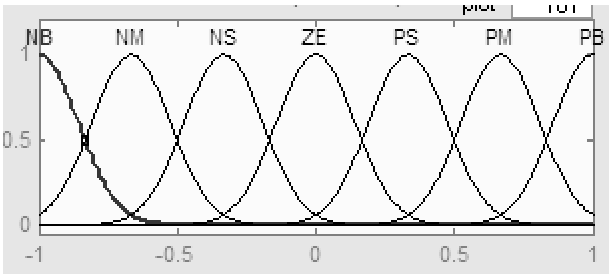


Figure-7. Membership function for error signal.

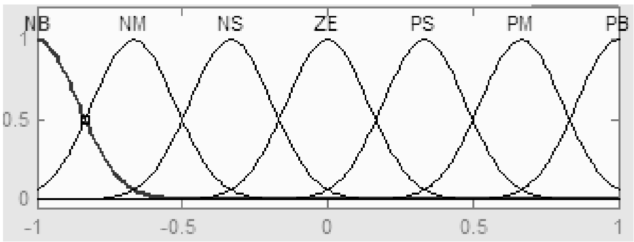


Figure-8. Membership functions for change in error signal.

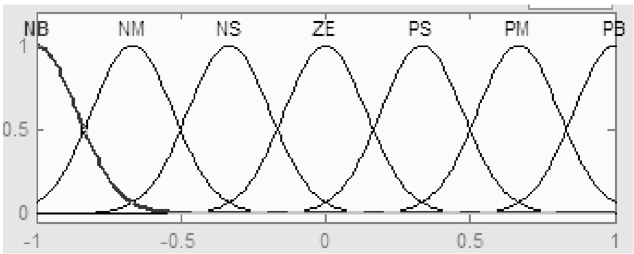


Figure-9. Membership function for control signal.

(c) **Fuzzification**

Fuzzification matches the input data with the conditions of the rules to determine how well the condition of each rule matches that particular input instance. It provides a mathematical way to represent vagueness in humanistic systems and is defined for each input and output variables in natural language. For ease of computation, seven fuzzy subsets [20] are defined by the library of fuzzy set values for the error and change in error and they are NB (Negative Big), NM (Negative Medium), NS (Negative Small), ZE (Zero), PS (Positive Small), PM (Positive Medium), and PB (Positive Big).

(d) **Development of rule base**

The collection of rules is called a rule base and it expresses input-output relationship in linguistic terms. There is no design procedure in fuzzy control such as root-locus design, frequency response design, pole placement design or stability margins because the rules are often non-linear and 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 (condition part) and consequent (operation part) are the description of process state and control output respectively in terms of a logical combination of fuzzy propositions. The generic linguistic control rule has the form as If x is A AND y is B THEN z is C where x,y are the input linguistic variables and z is the output linguistic variable. A, B and C are the fuzzy subsets in the Universe of discourses X, Y and Z respectively [14]. 49 rules as shown in Table-2 are formed depending on the number of membership functions to play a key role in the improvement of system performance.

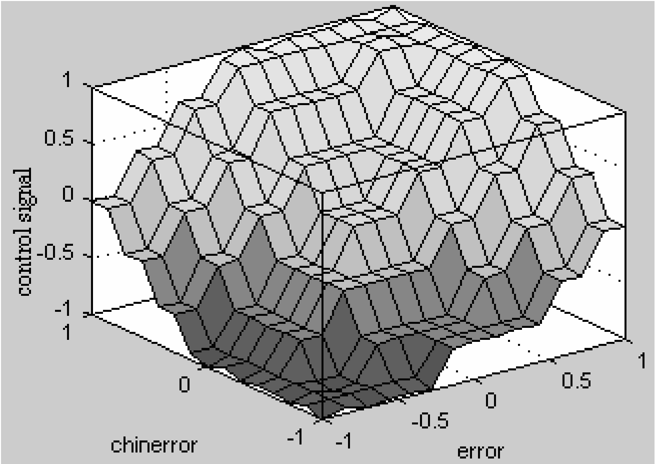


Figure-10. Rule base in terms of surface view.

Table-2. Rules for control signal.

ce e	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

(e) **De-fuzzification**

Conservation of the fuzzy to crisp or non-fuzzy output is defined as De-fuzzification. Mean of Maxima (MOM) method is implemented, where only the highest membership function component in the output is considered. This method disregards the shape of the fuzzy set but the computational complexity is relatively good.

5. DESIGN DATA

To compare the performance of Fuzzy controller with Buck converter and Quasi-Resonant Buck Converter, aforesaid controller as in Figure-11 with the specifications given in Table-3 is considered with the design constraints as mentioned hereunder [1].

- The rating of filter components must be much higher than the rating of the resonating components.
- The switching frequency must be higher than the natural frequency of the low pass filter at the output and so the state variables of filter state can be regarded as constant in each cycle.

Table-3. Design parameters.

No.	Parameter	Symbol	Value
1	Input Voltage	V_g	100 – 120 V
2	Output Voltage	V_o	54 V
3	Resonant Inductor	L_r	1.6 µH
4	Resonant Capacitor	C_r	0.064 µF
5	Filter Inductor	L_o	0.2 mH
6	Filter Capacitor	C_o	20 µF
7	Load Resistance	R	10 – 100 Ω
8	Normalized Impedance	Z_n	5 Ω
9	Switching Frequency	f_s	200 kHZ
10	Natural Frequency	f_o	2.5165 kHz
11	Resonant Frequency	f_r	0.5 MHz
12	Load Current	I_o	0.54- 5.4 A
13	Peak Resonant Current	I_M	20 A
14	Output Power(max)	P_O	2.916 kW

The output voltage of converter V_O is compared with the reference input V_{ref} and the error enters the controller in the forward path of the feedback system. If there is a deviation, the controller executes the rules and computes a control signal depending on the measured inputs namely error and change in error in order to provide the desired dynamic characteristics of the system.

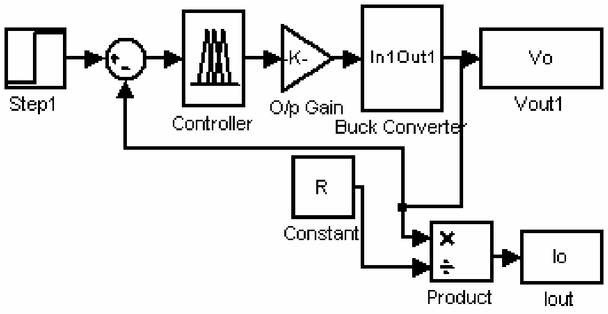


Figure-11. Single input single output negative feed back fuzzy controller.

i. 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 set point quickly.
ii. If the output is approaching the set point, a small change of the duty cycle is necessary.
iii. If the output is near the set point and is approaching it rapidly, the duty cycle must be kept constant so as to prevent overshoot.
iv. 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.
v. If the set point is reached and the output is steady, the duty cycle remains unchanged.
vi. If the output is above the set point, the sign of change of duty cycle must be negative and vice-versa.

6. SIMULATION

The transfer function of the Quasi Resonant Buck converter is represented as

$$\frac{\hat{v}_o}{\hat{v}_g} = \frac{M\left(1-\frac{J_i}{H_i}\right)}{s^2 L_o C_o + s\left(\frac{L_o}{R} - RC_o\frac{J_i}{H_i}\right) + 1 - \frac{J_i}{H_i}} \qquad (2.0)$$

Whereas the transfer function of Buck converter [21] depicted in Figure-12 is represented as

$$\frac{\hat{v}_o}{\hat{v}_g} = \frac{M}{s^2 L_o C_o + s\left(\frac{L_o}{R}\right) + 1} \qquad (2.6)$$

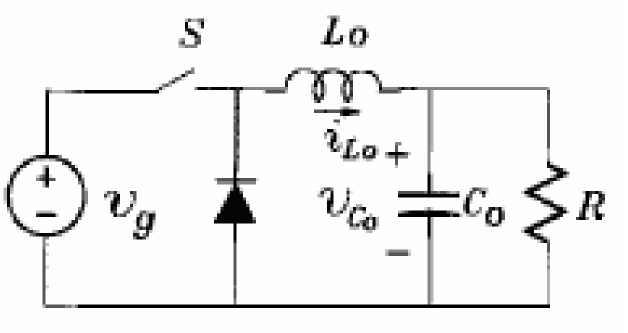


Figure-12. Buck converter.

The J/H parameter can be varied from -1 to 0 for the half - wave configuration. To compare the performance of five different operating points spanning the entire operating range of the converter have been selected [10].

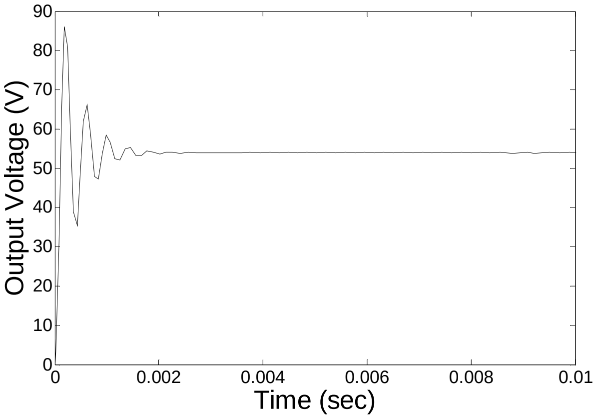
a) Minimum line and maximum load condition
b) Minimum line and light load condition
c) mid range line and load condition
d) Maximum line and maximum load condition
e) Maximum line and light load condition

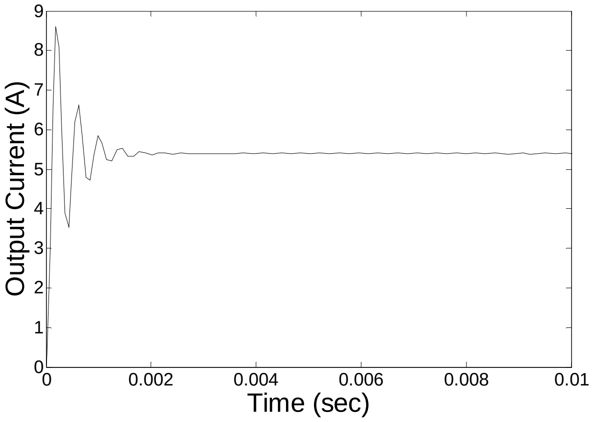
The results of digital simulation for J/H parameter equal to 0.0 and -0.2 for various conditions of supply and load variations are shown hereunder; J/H parameter = 0.0 depicts the result of digital simulation of Fuzzy control of

Buck Converter and that of -0.2 depicts Quasi-Resonant Buck Converter. It is shown that Fuzzy control of Quasi-Resonant Buck Converter gives better performance of voltage regulation. The output voltage of this converter at 54 V for varying conditions of operation is illustrated in Table-4.

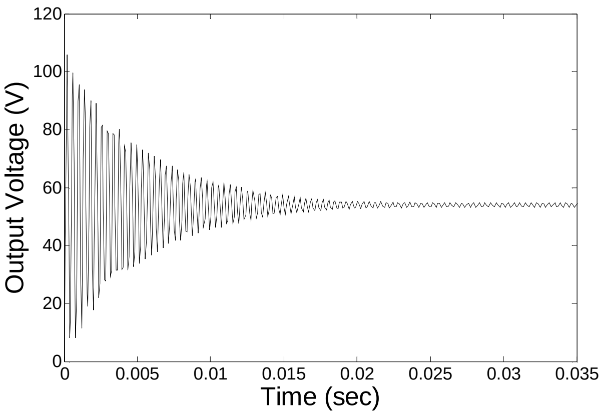
J/H Parameter = 0.0

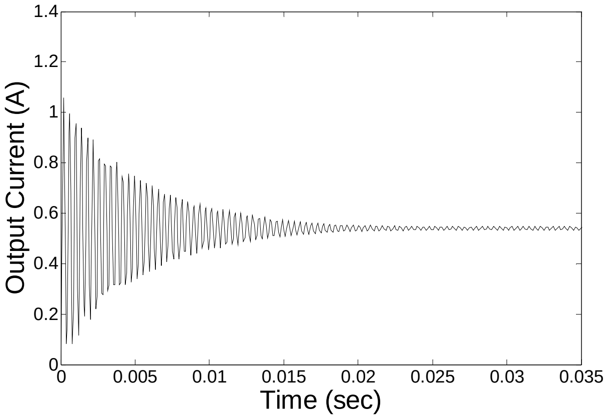
Case-1. Minimum Line and Maximum load condition.



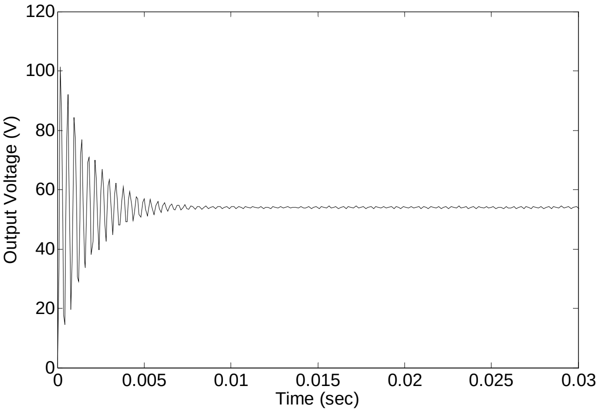


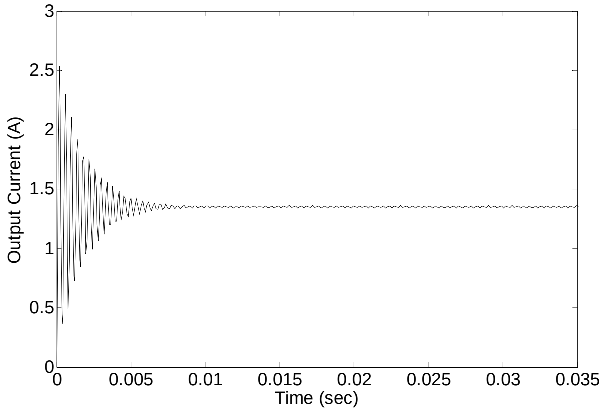
Case-2. Minimum line and light load condition.



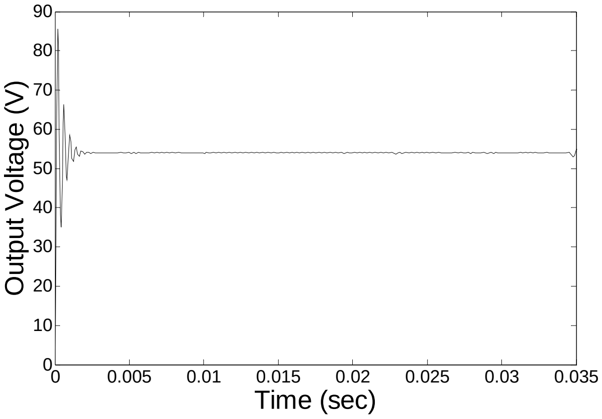


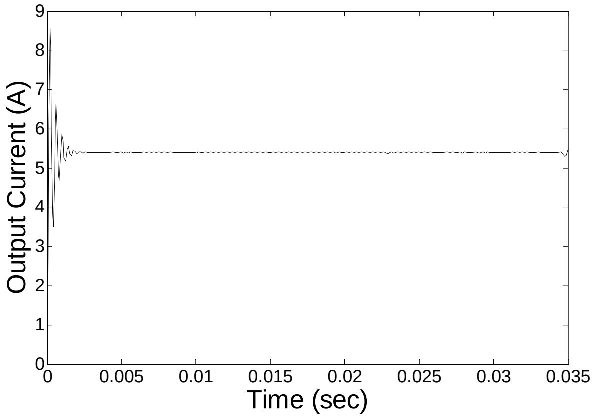
Case-3. Midrange line and load condition.



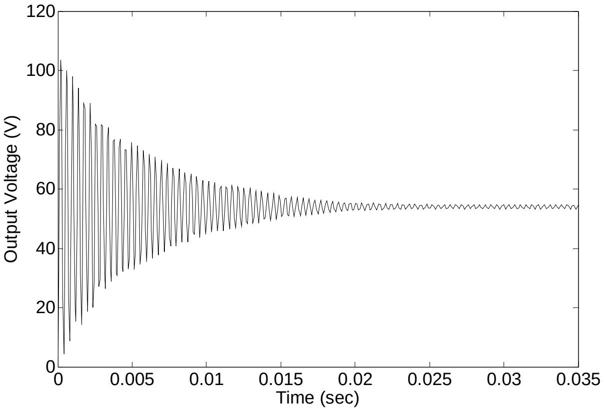


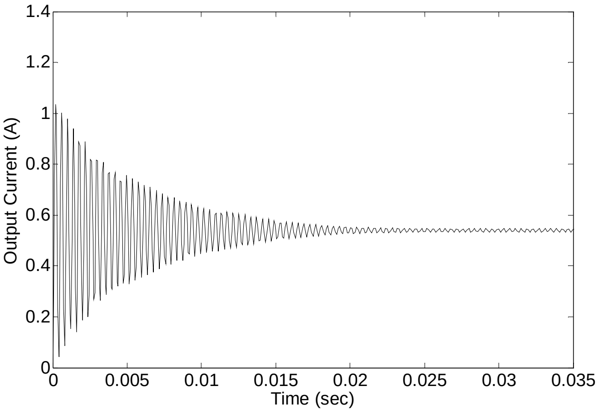
Case-4. Maximum line and maximum load condition.





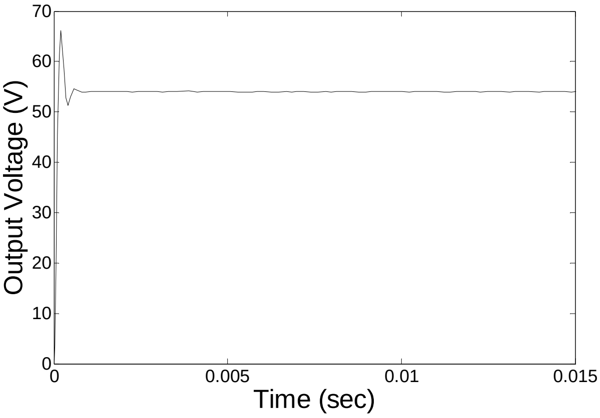
Case-5. Maximum line and light load condition.

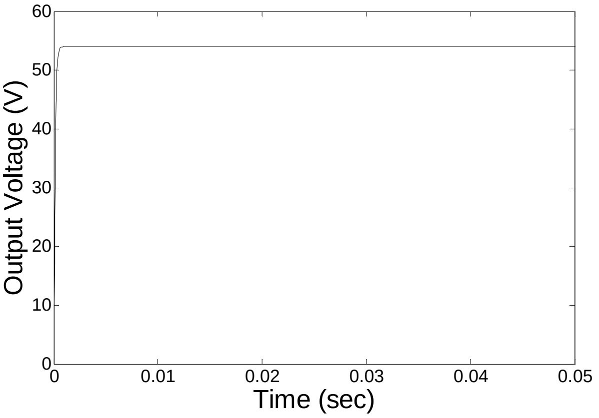




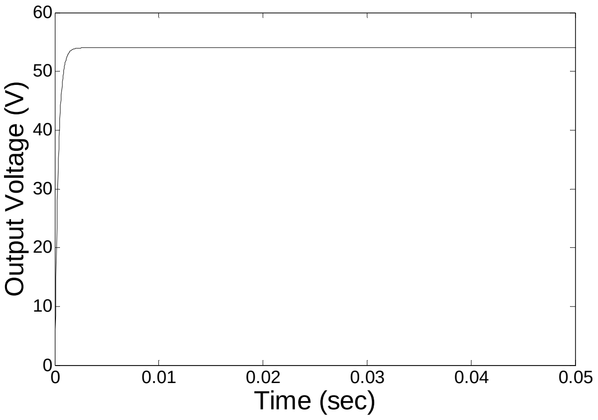
J/H Parameter = -0.2

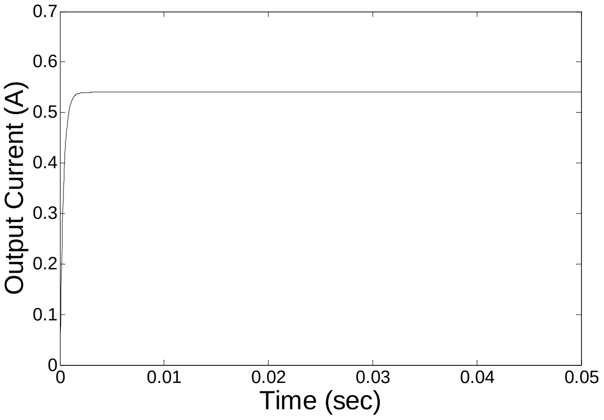
Case-1. Minimum line and maximum load condition.



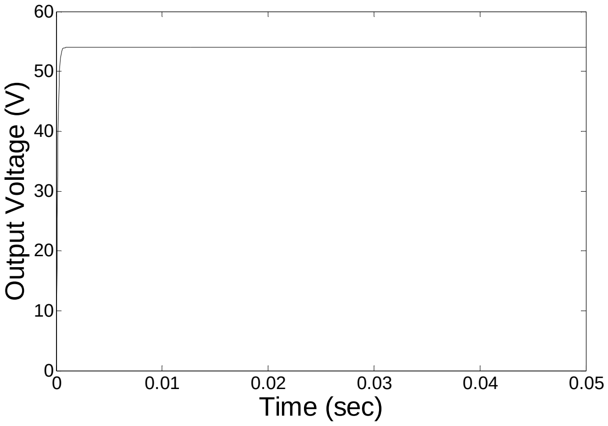


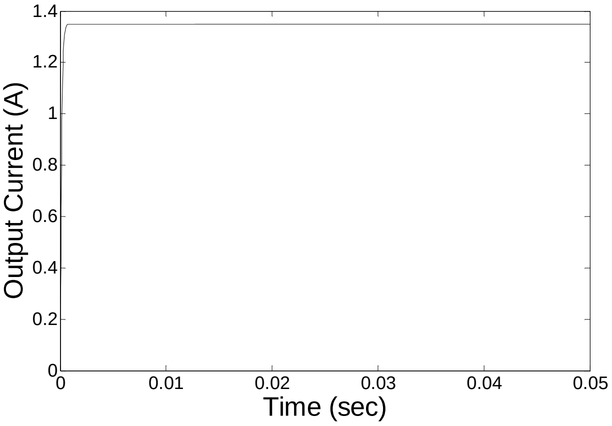
Case-2. Minimum line and light load condition.



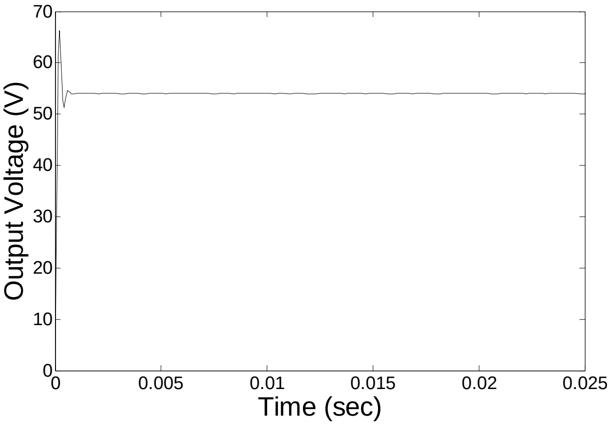


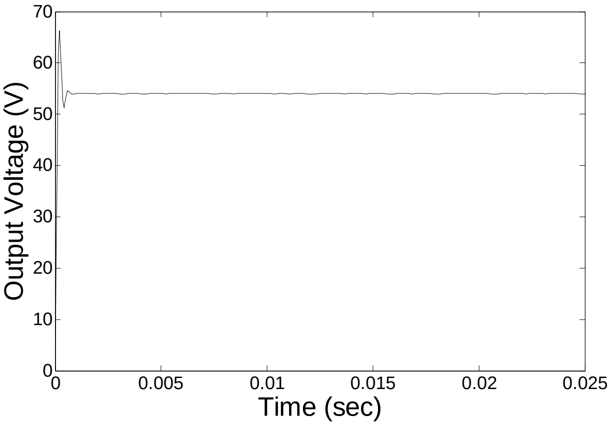
Case-3. Midrange lne and load condition.



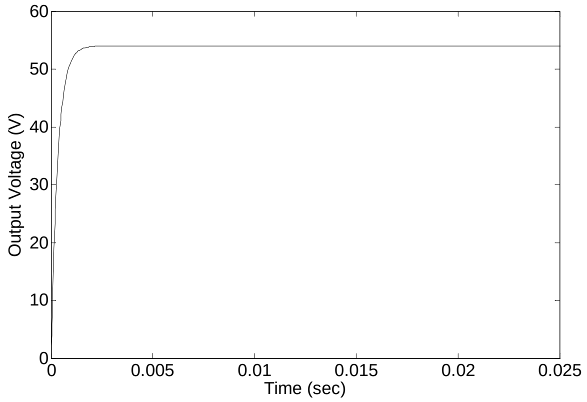


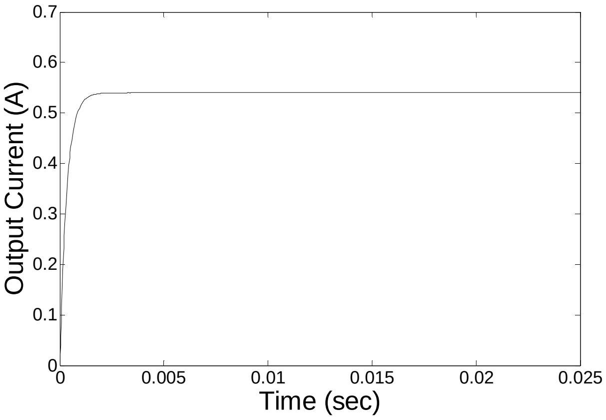
Case-4. Maximum Line and Maximum load condition.





Case-5. Maximum Line and Light Load condition.





The value of peak overshoot and settling time for J/H parameter equal to 0.0 and -0.2 for various conditions of supply and load variations is mentioned in chronological order in Table-5.

Table-4. Output voltage of the resonant buck converter.

Case	Input Voltage	Load Resistor	Load Current	Output Voltage
1	100	10	5.4	54
2	100	100	0.54	54
3	115	40	1.35	54
4	120	10	5.4	54
5	120	100	0.54	54

Table-5. Time domain specifications of the converter.

Case	Maximum overshoot		Settling time (ms)	
	Buck converter	QR buck converter	Buck converter	QR buck converter
1	86.122	66.221	1.3488	0.49053
2	105.84	54.003	20.362	1.3111
3	101.41	53.998	6.4845	0.50706
4	85.521	66.2635	1.3402	0.49143
5	103.64	53.9996	21.593	1.2819

7. CONCLUSIONS

A novel Fuzzy control scheme is implemented to improve the dynamic performance of the Quasi-Resonant Buck Converter. The Converter is simulated by MATLAB Software to show its feasibility and its transient characteristics are compared with the conventional Buck converter. Fuzzy Controller is able to regulate the output voltage to a desired value effectively for each operating point without steady state oscillations despite variations in load or input voltage and gives an improved performance compared to Buck Converter. As compared to standard controllers it has low electromagnetic interference as there are no very sharp edges of current and voltage waveforms, improved performance in maximum peak overshoot and settling time to parameter variations and better stability. The results obtained by simulation confirm the validity of the technique used.

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