

An Adaptive Fuzzy PID Control of Zero Current Switching Resonant Buck Converter

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ABSTRACT: In this paper, an auxiliary circuit to achieve the soft switching condition for a buck converter is proposed. The switching devices used in power converters need to withstand high voltage stress across them which leads to increased switching losses. In order to maximize the efficiency, soft switching techniques must be adopted. The performance of the converter is enhanced by introducing fuzzy PID controller. The performance of the proposed converter is compared with the fuzzy controller. The model is simulated in MATLAB/SIMULINK.

KEYWORDS: Soft Switching, Buck Converter, Fuzzy PID Controller.

I. INTRODUCTION

Buck converter is a step down DC-DC converter that widely being used in different electronic devices like laptop, PDAs, cell phones and also in electric vehicles to obtain different levels of voltages which is less than the input voltage[2]. In all of these applications, power conversion is required retaining high efficiency as much as possible. These converters essentially just change the input energy into a different impedance level [2]. However, the higher input voltages and lower output voltages have brought about very low duty cycles, increasing switching losses and decreasing conversion efficiency.

Pulse width modulated (PWM) DC/DC converters are vastly used in industry because of their high power capability and fast transient response [1]. To minimize the volume and weight of the converters, there is a need of higher switching frequency. In high power applications, switches are subjected to high switching stresses and switching losses, which limit the operating switching frequency [1]. To improve the efficiency, soft-switching techniques are widely applied to DC- DC converters. Resonant and quasi-resonant converters belong to family of soft-switching converters in which, resonance occur in the switch current or the voltage. When the switch current or voltage reaches zero, the switch can be turned on or off under soft-switching condition.

Although the power converters exhibit promising performance in power handling capability, they suffer with the inherent drawbacks such as electromagnetic interference (EMI), limitations maximum switching frequency and current spikes. In order to limit these effects, resonant tanks are incorporated in conventional PWM converters [1]. This facilitates the reduction in switching losses and improves the switching frequency. As an improvement soft switched converters which have the advantages of both conventional PWM converters and resonant converters were developed [2] - [4]. The major limitation in ZVS technique is requirement of the larger value of external resonating capacitor to minimize the turn off switching loss. ZCS eliminates the voltage and current overlap by forcing the switch current to zero before the switch voltage rises [1]-[4].

The paper is organized as follows. Section II deals with the literature survey of the proposed system. Section III explains about the design of the zero current switching resonant buck converters. The design of control circuits using fuzzy PID controller in section IV. The simulation results are presented in section V and finally section VI presents the conclusion.

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II. RELATED WORK

A lot of researches are going on, for improving the performance of the converters. Nowadays uses of converters are widely increasing. There are application varying from medium voltage to high voltages which are required for DC-DC conversion. Each day a new idea is being put forward. The following papers contributed a lot in understanding about the further modifications.

In [1] an auxiliary circuit to achieve soft switching condition for a buck converter is introduced. The switching devices used in power converters need to withstand high voltage stress across them which leads to increased switching losses. In order to maximise the efficiency soft switching techniques were used. The performance of the converter is enhanced by introducing fuzzy logic controller.

A zero current switching resonant buck converter as a soft switching DC-DC converter is explained in [4]. Also, the converter benefits from a very simple control method. In this buck type converter uses auxiliary switches. In the proposed converter both switches are turned on/off under zero current switching condition and thus the topology is suitable for employing IGBT for high power. The diode turns on under zero voltage condition and turns off at zero current condition. Thus, all semiconductor elements are soft switched.

A robust sliding mode controller for the control of DC-DC buck converter is described in [5]. A two-loop control is employed for a buck converter. The robustness of the sliding mode controlled buck converter system is more for step load changes and input voltage variations. Fast dynamic response of the output voltage, robustness to the load and input voltage variations were obtained. In the sliding mode the converter is insensitive to parameter uncertainties, variations and unknown disturbances. Thus a robust output voltage can be obtained.

An open loop and closed loop digital PID controller using microcontroller for the control of buck converter is described in [6]. The controller is used to change the duty cycle of the converter and thereby, the voltage is regulated. The transient performance and steady state performance is improved using PID controller. The experimental system is more advantageous and cost effective with microcontroller.

In [7] introduced a new family of soft switching Pulse Width Modulation (PWM) converters. In this family of converters, two switches operate out of phase and share the output current while providing soft switching condition for each other. Regular PWM control circuit is added to the converter for providing gating signals for the switches.

A family of switched capacitor resonant circuits using only two transistors is mentioned in [10]. The circuit operates under zero current switching and thus the switching loss is zero. It also offers a wide choice of voltage conversions including fractional as well as multiple and inverted voltage conversion ratios.

III. ZERO CURRENT SWITCHING RESONANT BUCK CONVERTER

In this section the proposed converter is introduced and analyzed. Consider the buck converter circuit shown in Fig.1.

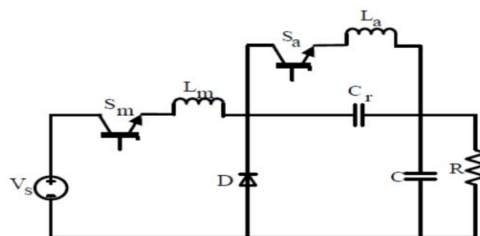


Fig. 1: Circuit diagram of proposed converter

The circuit consists of two switches, main switch S_m and the auxiliary switch S_a , one diode, main inductor L_m , auxiliary inductor L_a , resonant capacitor C_r and one output capacitor C which is meant for reducing ripples in the output voltage. The circuit is connected to a DC supply and the load is resistive. Both the switches can be operated at ZCS.

At the steady state condition, the converter voltage gain, A can be calculated by considering the converter efficiency equal to 100%. In this converter, energy is absorbed from the input source only in the first interval. Thus, the voltage gain can be calculated using this fact. For the first interval the following relations can be derived.

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$$E_{in} = \int_{t_1}^{t_6} V_s I_{Lm} dt \tag{1}$$

$$E_{out} = \frac{V_{out}^2 T}{R} \tag{2}$$

$$E_{in} = E_{out} \tag{3}$$

$$A = \frac{V_{out}}{V_{in}} = \sqrt{2C_r R f} \tag{4}$$

From buck converter design rules,

$$L_m = \frac{V_o(1-D)}{f\Delta I} \tag{5}$$

$$C_m = \frac{\Delta I}{8 f \Delta V} \tag{6}$$

With increase in the frequency, the transferred power increases, but frequency is restricted to two resonant periods.

$$T_{min} = a_{1min} + a_{2max} = \pi\sqrt{L_m C_r} + \pi\sqrt{L_a C_r} = \frac{1}{f_{max}} \tag{7}$$

The input and output voltages of the converter are 100V and 50V respectively. The output current is about 1.2A. The switching frequency is about 25KHz. The main and auxiliary inductors are about 2.77mH and 0.28mH. The resonant is 0.12µF. The output filter capacitor is chosen as 50µF for 1% ripple in output voltage. The design values are shown in table I.

TABLE I: DESIGN VALUES OF ZCS BUCK CONVERTER

Parameter	Value
Input Voltage	100 V
Output voltage	50 V
Output current	1.2 A
Switching frequency	25 KHz
Main inductor	2.77 mH
Auxiliary inductor	0.28 mH
Resonant capacitor	0.12 µF
Output capacitor	50 µF

IV. DESIGN OF CONTROL CIRCUIT USING FUZZY PID CONTROLLER

Fuzzy logic is a problem solving technique in control system which uses if else logic. Fuzzy concept was introduced by Zadeh [14]. This concept is based on partial set membership rather than crisp set membership. Adaptation of this logic is used here for online tuning of PID and referred as fuzzy logic based PID controller. Fuzzy PID has been widely used in the research due to its major advantage over conventional PID controller, the capability to update the controller parameters in real time whereas in conventional PID parameters are fixed. In the system, by taking error and change in

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error as input, the method of fuzzy Inference can be used to make online self-tuning of PID parameter K_p , K_d and K_i [14]. Accordingly, the static and dynamic performance of the controlled object can be improved well. K_p , K_d , K_i are parameters that characterize the proportion, integral and differential role respectively.

1) Membership Functions:

Membership function defines the fuzziness in a fuzzy set irrespective of the elements in the set, which are discrete or continuous. The membership function is generally represented in graphical form. There exists certain limitation for the shapes used to represent the membership function. A membership function can be thought of as a technique to solve empirical problems on the basis of experience rather than knowledge.

Fuzzy controller which used to parameter adjustment of PID uses form of two inputs and three outputs. Inputs of the controller are error E and error ED , and outputs are K_p , K_i , K_d which are revised by three parameters of PID controller as P , I , D . Fuzzy subset of inputs as e and de and outputs as K_p , K_i , K_d is $\{NB, NM, NS, ZO, PS, PM, PB\}$.

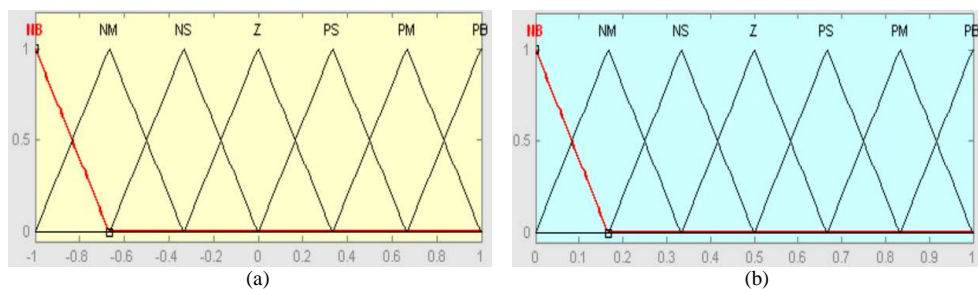


Fig.2: a) The membership function of E and ED b) The membership function of K_p , K_i , K_d

In the fuzzy logic toolbox of the membership function editor, trimf is selected by membership functions of input as E , ED and also for the membership functions of output as K_p , K_i , K_d as shown in Fig.2.

2) Development of Rule Base:

The general way of representing human knowledge is by forming natural language expressions given by: IF antecedent THEN consequent. This is termed as IF-THEN rule based form. The fuzzy rules are formed using IF-THEN statements and AND/OR connectives. The outputs of fuzzy rules are combined to obtain one fuzzy output distribution. From, fuzzy inference system, it is desired to get only one crisp output. The crisp output may be obtained from defuzzification process. The common techniques of defuzzification used are centre of mass and mean of maximum. Rules for K_p , K_i and K_d are as shown in table II, table III, table IV respectively, are formed depending on the number of membership functions to play a key role in the improvement of system performance. The linguistic terms correspond to NB (Negative Big), NM (Negative Medium), NS (Negative Small), ZE (Zero Equal), PS (Positive Small), PM (Positive Medium), and PB (Positive Big).

The center of fuzzy control is to build proper fuzzy rules chart based on the summary of designers knowledge and operating experience. According to the PID parameter adjustment principles above, the control rules of K_p , K_i and K_d as shown in Table II.

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TABLE II: FUZZY RULES FOR a) CHANGE IN K_p b) CHANGE IN K_i c) CHANGE IN K_d

E\ED	NL	NM	NS	ZE	PS	PM	PL	E\ED	NL	NM	NS	ZE	PS	PM	PL	E\ED	NL	NM	NS	ZE	PS	PM	PL
NL	PL	PL	PL	PL	PL	PL	PL	NL	NL	NL	NL	NL	NL	NL	NL	NL	NL	NL	NL	NL	NL	NL	NL
NM	PS	PM	PM	PM	PM	PM	PS	NM	NM	NL	NL	NL	NL	NM	NM	ZE	NS	NM	NM	NM	NS	ZE	
NS	ZE	ZE	PS	PS	PS	ZE	ZE	NS	PM	ZE	NM	NL	NM	ZE	PM	NS	PS	ZE	ZE	ZE	ZE	ZE	PS
ZE	NL	NS	ZE	ZE	ZE	NS	NL	ZE	PL	PM	PS	NL	PS	PM	PL	ZE	PL	PL	PM	PS	PM	PL	PL
PS	ZE	ZE	PS	PS	PS	ZE	ZE	PS	PM	ZE	NM	NL	NM	ZE	PM	PS	PS	ZE	ZE	ZE	ZE	ZE	PS
PM	PS	PM	PM	PM	PM	PM	PS	PM	NM	NL	NL	NL	NL	NM	PM	ZE	NS	NM	NS	NM	NS	ZE	
PL	PL	PL	PL	PL	PL	PL	PL	PL	NL	NL	NL	NL	NL	NL	PL	NL	NL	NL	NL	NL	NL	NL	

a)

b)

c)

The desired output voltage and the actual output voltage are compared and an error signal is generated. The inputs to the fuzzy logic controller are error and change in the error. The change in the error is computed by using the present and the past values of the error of K^{th} as given by,

$$ED = e(k) - e(k-1) \tag{8}$$

The fuzzy controller produces three outputs K_p , K_i and K_d . These values are fed to the PID controller and thus online tuning of the PID controller is achieved. The output of the PID controller is a controlled signal which acts as the set point of duty cycle. This signal is compared with repeating sequence which is a saw tooth wave. Whenever the amplitude of the output of PID controller is greater than the amplitude of repeating sequence an on-going pulse is generated. Similarly, when the output from PID controller is less than the amplitude of repeating sequence, an off-going pulse is generated.

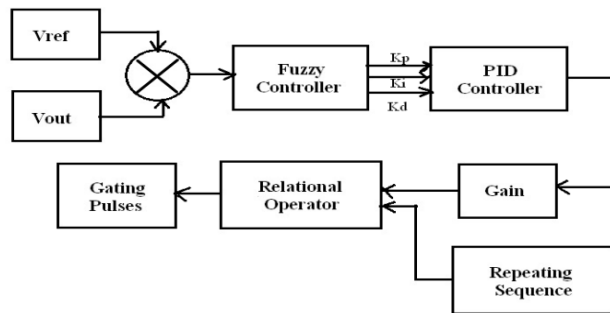


Fig.3: Control circuit using fuzzy PID controller

In this way, the pulse pattern for the switches can be obtained. The control circuit is shown in Fig.3.

V. SIMULATION RESULTS

The ZCS buck converter circuit model is simulated in MATLAB/SIMULINK which is shown in Fig.4 and their control circuit with fuzzy is shown in Fig.5. Initially the simulation is done with the normal fuzzy controller and the same circuit is also simulated with the fuzzy PID controller. The circuit diagram remains the same for both the controllers, only the control circuit changes.

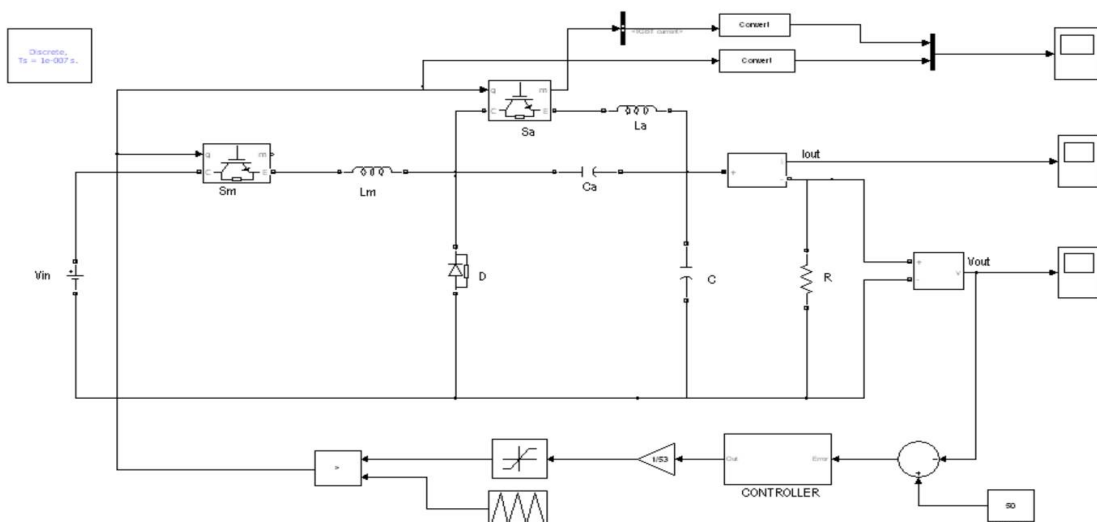


Fig: 4: Simulation diagram for the ZCS buck converter

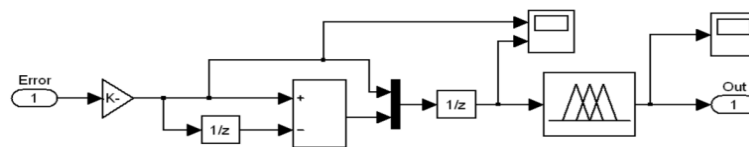


Fig: 5: Simulation diagram for the control unit of fuzzy controller

Fig. 6.a) shows the waveforms for the output voltage and Fig.6.b) shows the output current of the fuzzy controlled ZCS buck converter. In both the output voltage and current waveforms there exists some sort of disturbances in the form of ripples and overshoot.

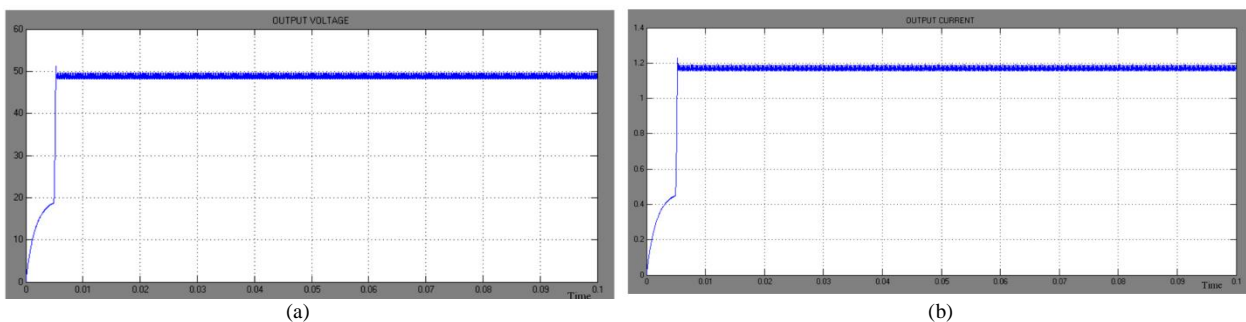


Fig. 6: a) Output voltage of ZCS buck converter using fuzzy controller b) Output current of ZCS buck converter using fuzzy controller

The control circuit for the ZCS buck converter using fuzzy PID controller is shown in Fig.7. The corresponding waveforms for the output voltage and output current are shown in Fig.8.

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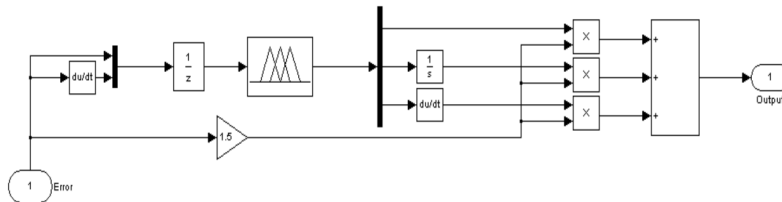


Fig: 7: Simulation diagram for control unit of fuzzy PID controller

The ripples in the output voltage and current are reduced to a great extent when fuzzy PID controller is used (in fig.8) when compared with the waveforms of the output voltage and current which uses the normal fuzzy controller (in fig.6).

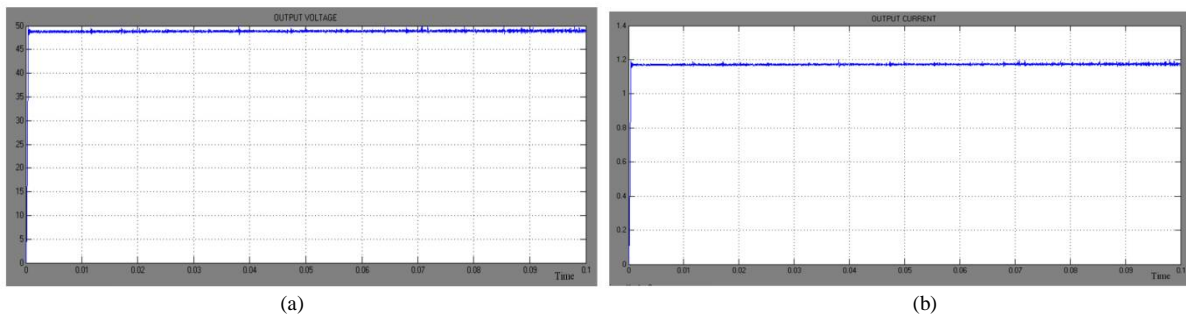


Fig. 8: a) Output voltage of ZCS buck converter using fuzzy PID controller b) Output current of ZCS buck converter using fuzzy PID controller

Table V represents the comparison between the performance of the ZCS buck converter using fuzzy controller and fuzzy PID controller. The parameters like settling time, rise time, peak voltage, ripples in output voltage and current, overshoot and efficiency is considered for the comparison.

TABLE III: COMPARISON BETWEEN THE PERFORMANCE OF BUCK CONVERTER USING FUZZY AND FUZZY PID CONTROLLER

Parameter	Fuzzy Controller	Fuzzy PID Controller
Settling Time	5.6 ms	0.71 ms
Rise Time	5.4 ms	0.45 ms
Peak Voltage	51.2 V	50.1 V
Ripples in Output Voltage	1.5 V	0.3 V
Ripples in Output Current	0.04 A	0.008 A
Overshoot	0.076 V	0.021 V
Efficiency	94.3 %	96.05 %

The performance of the converter is improved with fuzzy PID controller than with the fuzzy controller. The settling time, rise time and peak voltage of the fuzzy PID controlled converter is much reduced than with those of the fuzzy controlled converter and also the ripple content gets reduced to a great extend. Thus the overall efficiency of the proposed converter is increased with the fuzzy PID controller.

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V. CONCLUSION

Soft switching techniques not only reduce the switching losses but also improve the efficiency of the converter. The overall performance of the fuzzy PID controlled buck converter is improved by reducing the settling time, rise time, peak voltage, ripples and overshoot when compared with the performance of fuzzy controlled buck converter. The tuning of the PID controller is made easy by using the fuzzy controller. In these soft switched converters resonance is allowed to occur just before and during the turn-on and turn-off processes so as to ensure ZCS condition. High efficiency power conversion can be achieved using fuzzy PID controller along with the ZCS topology.

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