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Closed Loop Control of Soft Switched Forward Converter Using Intelligent Controller

M.V. Sudarsan* Ch. Saibabu and S. Satyanarayana*****

Abstract : A tight voltage regulation is required in the power supply units in power electronic equipments and is achieved with closed loop operation. In this paper, the closed loop control of zero-current soft switched pulse width modulation based forward converter is implemented using the intelligent controller namely, fuzzy logic controller. The zero current switching (ZCS) for the main switch of forward converter is achieved by a simple auxiliary circuit consisting of an auxiliary switch and capacitor on secondary side of transformer, also the auxiliary circuit is used to reset the transformer core. Another advantage of this converter over conventional ZCS forward converter is that additional inductor is not required to reset the transformer core and the leakage inductance of transformer itself is used as a resonant inductor. The auxiliary switch is also soft switched. Thus the soft switched forward converter is operated in closed loop for obtaining the desired output voltage by having a control over duty ratio of the main switch by designing the intelligent fuzzy logic controller. The MATLAB simulation results of this soft switched converter shows the better performance using fuzzy logic controller over the conventional PI controller in closed loop operation.

Keywords : Forward converter, soft switching, PWM technique PI controller and fuzzy logic controller.

1. INTRODUCTION

In various applications, there is a necessity of dc power supplies which is fulfilled by the isolated converters namely, fly back and forward converters. These are mostly used in low power applications because of small count in elements and simple in structure. High voltages are observed across the switch during turn off period, due to the transformers leakage inductance. The voltage spikes and switching losses can be reduced by using RCD (resistor-capacitor-diode) clamps and snubbers. The zero voltage switching and zero current switching conditions are achieved for forward converters by using active snubber and clamps. Many methods are introduced to provide ZCS for main and auxiliary switches, but these methods require a reset winding and inductor in the auxiliary circuit [12] and [13]. Even then the main switch is not fully soft switched because of presence of large magnetizing inductance during turn off instant. In addition to reduce the switching losses, the voltage is to be controlled as per the requirement. Thus the soft switched converter is operated in closed loop with fuzzy logic controller.

Fuzzy logic is a departure from classical Boolean or crisp logic as it relies on human capability to understand system's behavior and is based on qualitative control rules and quantitative mathematical theory. It is one of the intelligent schemes that convert the linguistic control strategy based on expert

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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. 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.

In this paper, a simple auxiliary circuit consisting of an auxiliary switch and auxiliary capacitor is used on the secondary side of isolated transformer of forward converter to provide ZCS condition. This ZCS condition is employed for both main switch and auxiliary switch also. Additional advantage of this converter is there is no need of using a reset winding and the leakage inductance of the transformer is used in resonance with the capacitor to reset the transformer core. As compared with active clamp method of soft switching this method is load independent, *i.e*, the auxiliary circuit elements are designed for nominal load, so that the zcs condition can be employed under any load conditions .Thus along with this soft switching the load output voltage is controlled by generating a required duty ratio from the fuzzy logic controller with closed loop operation. Fig.2 shows the block diagram of controlling of the ZCS operated forward converter. The converter is analyzed in section-II. closed loop operation for this converter is discussed in section-III and the simulation study of this soft switched converter in closed loop is discussed in section-IV.

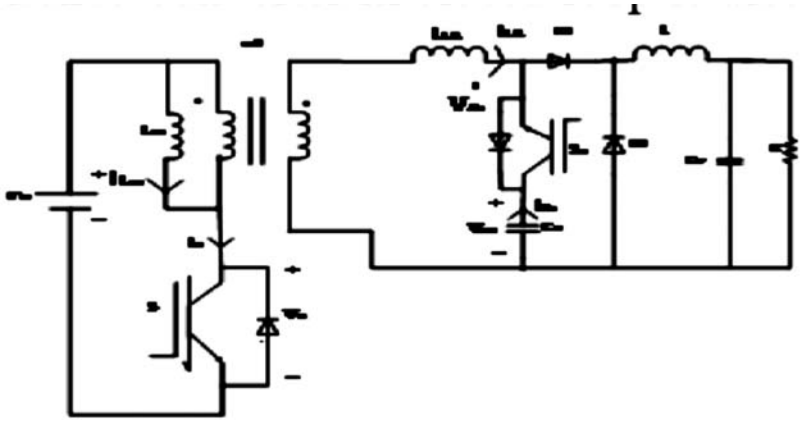


Fig. 1. ZCS soft switched forward converter with auxiliary circuit.

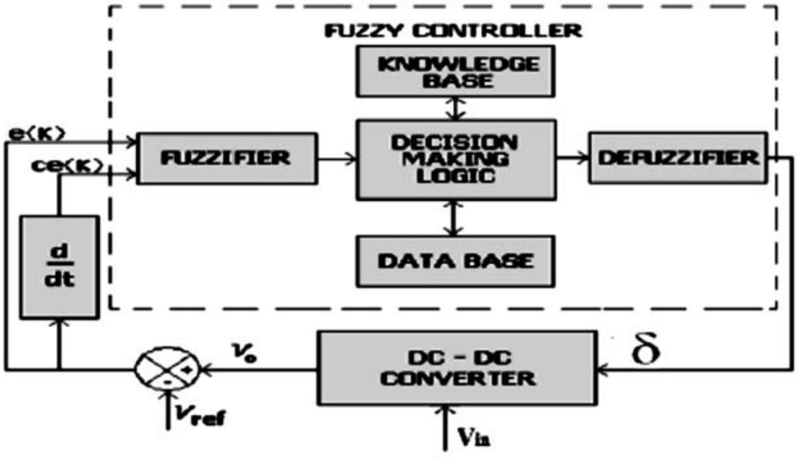


Fig. 2. Block diagram of the converter with Fuzzy logic Controller.

2. MATHEMATICAL ANALYSIS OF ZCS FORWARD CONVERTER

The soft switched converter with the simple auxiliary circuit consists of main switch Sa, Diodes D_1 and D_2, Filter inductance L, ideal transformer T with n : 1 turns ratio, leakage inductance L_l and magnetizing inductance L_m. The auxiliary circuit having elements are auxiliary switch S_a and auxiliary capacitor C_a. For simple analysis, input voltage is considered as constant and is equal to Vin and also output inductor current is assumed constant and is equal to Io. Thus the operation of this soft switched converter is explained in ten modes over a switching cycle. The following assumptions are made before analyzing the operation of the circuit as C_a charged to 2Vin/n. The auxiliary switch is off and the diode D_1 and main switches are conducting.

Mode 1 [$t_0 - t_1$] : In this interval, the main switch conducts and carries a current of Io/n + I_{lm}. This mode starts with the auxiliary switch turn on and begins the resonance condition between auxiliary capacitor and leakage inductance and transformer. As the capacitor voltage is greater than Vin/n, the leakage inductance of current of the transformer (I_{lk}) falls to zero and the main switch current also decreases to I_{lm}. Thus the leakage inductance current and the voltage of auxiliary switch in the mode are defined as Equation 1, 2 & 3.

$$I_{LL} = I_0 - \frac{\left(2V_{in}/n\right) - \left(V_{in}/n\right)}{z_0}\sin(w_0(t - t_0)) \tag{1}$$

$$Vc_a = \frac{V_{in}}{n} + \left(\frac{2V_{in}}{n} - \frac{V_{in}}{n}\right)\cos(w_0(t - t_0)) \tag{2}$$

where

$$Z_0 = \sqrt{\frac{L_L}{C_a}}, w_0 = \frac{1}{\sqrt{L_L C_a}} \tag{3}$$

Mode 2 [$t_1 - t_2$] : In this interval, the resonance between the leakage inductance and auxiliary capacitor continues and makes the leakage current negative. This in term falls, the main switch current from I_{lm} to zero. This mode ends by observing the leakage inductor current falls to $-nI_{lm}$. (Thus the same equations are applied for inductance current and capacitor voltage in this mode also).

Mode 3 [$t_2 - t_3$] : In this interval of operation, the magnitude of leakage inductance current is higher. Then nI_{Lm} with the opposite direction and the body diode of the main switch conducts current. Then, in the period, the main switch can be turned off with ZCS condition. Thus, the same equations are applied for inductance current and capacitor voltage in this mode also.at the end of this mode, the auxiliary capacitor voltage reaches to V_1, which is less than Vin/n and $-nI_{lm}$ is the current into leakage inductance at the end of the interval.

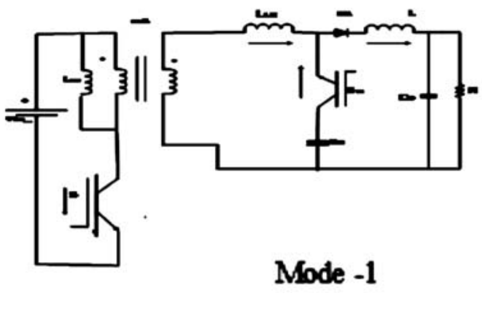


Fig. 3. Equivalent circuit of the converter in mode 1.

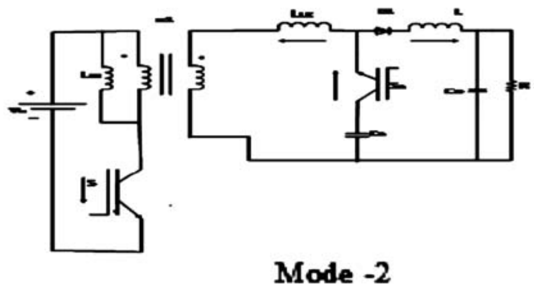


Fig. 4. Equivalent circuit of the converter in mode 2.

Mode 4 [$t_3 - t_4$] : In this interval, the leakage inductance current is constant and equals to $-nI_{lm}$,the auxiliary capacitor discharges with constant current equal to nIlm + I_0 until its voltage becomes zero. This mode ends when V_{ca} reaches to zero. Then the diode D_2 is forward biased and starts carrying current at zvs. Thus, at the end of this mode diode D_1 turns off at ZVS.The auxiliary capacitor voltage in this mode is given by equation (4).

$$Vc_a = V_1 - \frac{I_0 + nI_{Lm}}{C_a}(t - t_3) \tag{4}$$

Mode 5 [$t_4 - t_5$] : In this interval, the resonance starts between the auxiliary capacitor and leakage inductance and magnetizing inductance of transformer. In this mode, during resonance L_m current falls to zero and thus resets the transformer core also D_2 conducts the output inductor current. The equations for magnetizing current and capacitor voltage in this mode are given by eq. (5), eq. (6) & eq. (7).

$$IL_m = \bar{I}_{Lm}\cos((w_1(t - t_4)) \tag{5}$$

$$Vc_a = -Z_1 n\overline{I_{Lm}}\sin(w_1(t - t_4)) \tag{6}$$

Where

$$Z_1 = \sqrt{\frac{L_m}{n^2 C_a}}, w_1 = \frac{n}{\sqrt{L_m c_a}} \tag{7}$$

The following assumptions are made before analyzing the operation of the circuit as C_a charged to 2Vin/*n*. The auxiliary switch is off and the diode D_1 and main switches are conducting.

Mode 6 [$t_5 - t_6$] : In this interval the resonance between auxiliary capacitor C_a and magnetizing inductance L_m continues through the body diode of auxiliary switch. The auxiliary capacitor voltage rises from its initial value $-nI_{lm}Z_1$ (then, the same equations are applied for inductance current capacitor voltage in this mode also. Therefore, at the end of the mode, the magnetizing inductance current is zero and C_a maintains constant voltage equals to $-nI_{lm}Z_1$. Therefore, at the end of the mode, the magnetizing inductance current is zero and C_a maintains constant voltage equals to $-nI_{lm}Z_1$.

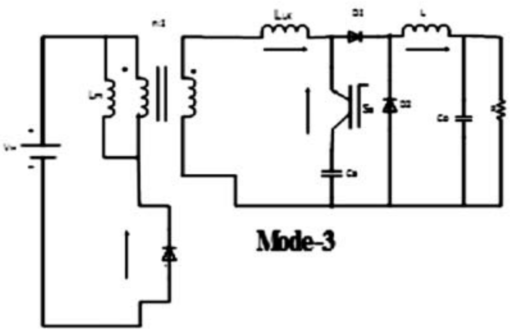


Fig. 5. Equivalent circuit of the converter in mode.

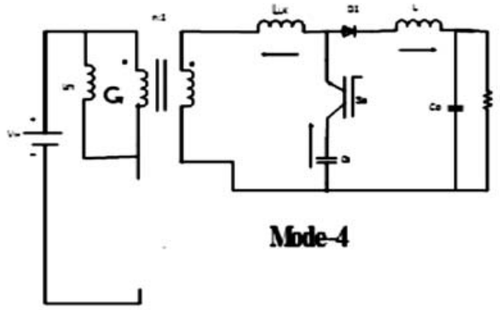


Fig. 6. Equivalent circuit of the converter in mode 4.

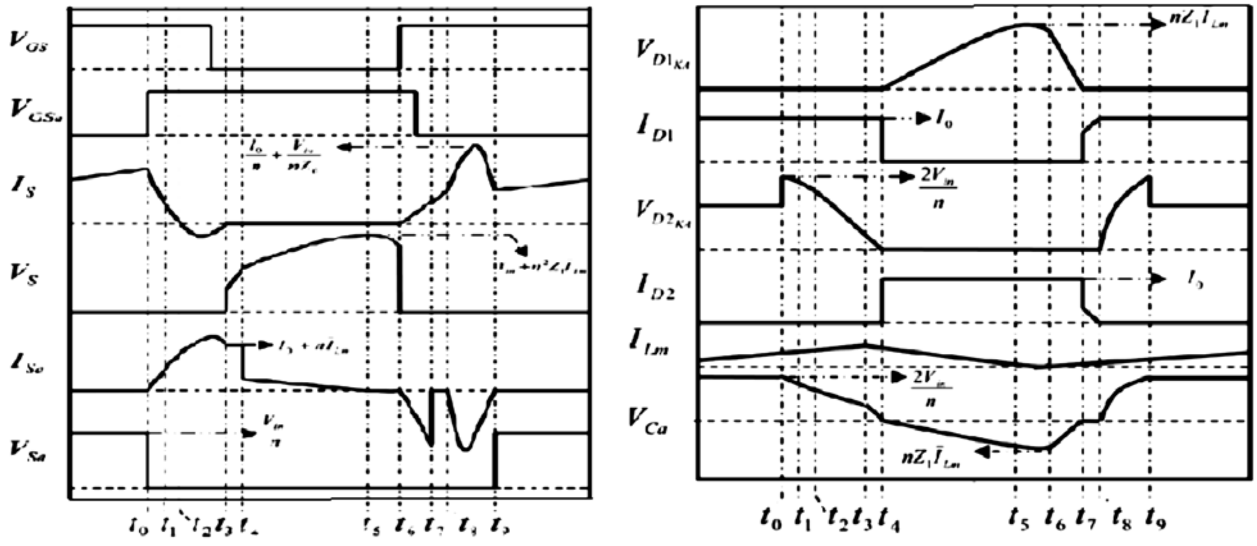


Fig. 7. Theoretical model waveforms of the converter.

Mode 7 [$t_6 - t_7$] : This interval starts by turn on of main switch. This makes the V_{in} placed across the transformer primary and resonance starts between the C_a and the transformer leakage inductance. The voltage of auxiliary capacitor rises from its negative value towards to zero and the current in leakage inductance of the transformer rises to I_1.

$$IL_L = \frac{\left(V_{in}/n\right) + z_1 \, nI_{L_m}}{z_0} \sin(w_0(t - t_6)) \tag{8}$$

$$Vc_a = Z_1 n\bar{I}_{L_m} + \left(\frac{V_{in}}{n} + Z_1 n\bar{I}_{Lm}\right) * (-\cos(w_0\,(t - t_6)) + 1) \tag{9}$$

Mode 8 [$t_7 - t_8$]: This interval starts when auxiliary capacitor voltage reaches to zero and diode D_1 starts conducting current. As diode D_2 is conducting, the capacitor voltage remains zero. In this mode, the secondary voltage is Vin / *n* and the leakage inductance current increases linearly from I_1 to I_0. At the end of this mode diode D_2 turns off. The leakage inductance current is given by

$$IL_L = I_1 + \frac{V_{in}(t - t_7)}{nL_L} \tag{10}$$

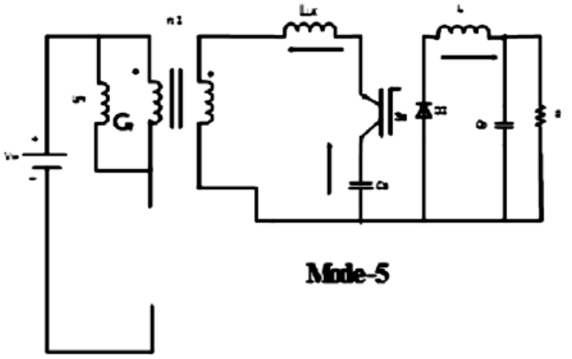


Fig. 8. Equivalent circuit of the converter in mode 5.

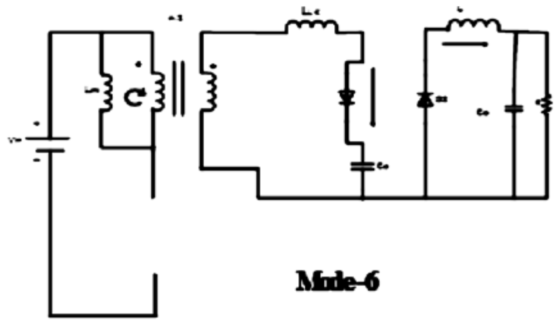


Fig. 9. Equivalent circuit of the converter in mode 6.

Mode 9 [$t_8 - t_9$] : In this mode of operation, the resonance is occurred with leakage inductance and capacitor through the body diode of auxiliary switch. Thus, the auxiliary switch S_a can be now turned off at any time during this interval under ZVS. At the end of this mode, the capacitor voltage C_a is equal to $2V_{in} / n$. Half of the resonance period formed by C_a and L_L is the duration of this interval. Thus, the equations for I_{LL} and V_{ca} is given by

$$IL_L = \frac{V_{in}}{nz_0} \sin(w_0(t - t_s)) \tag{11}$$

$$Vc_a = V_{in} - V_{in} \cos\,(w_0(t - t_s)) \tag{12}$$

Mode 10 [$t_9 - t_0 + T$] : The main switch is turned on in this mode and the converter operates like a normal PWM forward converter. Duration of this mode is D*T. where D is the duty ratio and T is the switching period. The equation for the magnetizing current at the end of this interval is given by

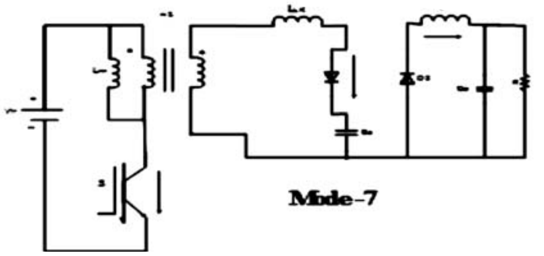


Fig. 10. Equivalent circuit of the converter in mode 7.

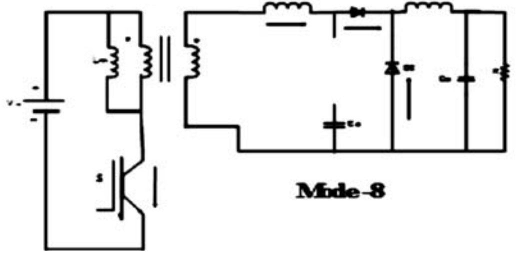


Fig. 11. Equivalent circuit of the converter in mode 8.

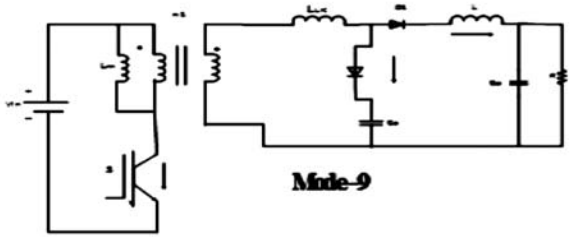


Fig. 12. Equivalent circuit of the converter in mode 9.

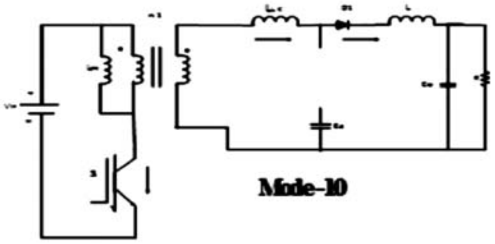


Fig. 13. Equivalent circuit of the converter in mode 10.

3. DESIGN OF THE ZCS FORWARD CONVERTER USING AN SIMPLE AUXILARY CIRCUIT

In this section the design of ZCS Forward converter, reducing the voltage from 150V to 32V operated at 100 KHz is given in detail. Table 1 shows the parameters of the ZCS forward converter with an auxiliary circuit.

Table 1. Parameters of the ZVS-QR Buck converter.

Parameter	*Symbol*	*Value*
Input voltage	V_s	150V
Output voltage	V_0	32V
Power	P_0	200W
Switching frequency	f_s	100 KHz
Magnetizing Inductance	L_m	1mH
Transformer turns ratio	$n : 1$	2
Duty cycle	D	0.45
Auxiliary capacitor	C_a	22nF
Leakage inductance in secondary side	L_l	2μH

As per the analysis of the converter in section II, the equation that should be satisfied to get the ZCS of the main switch in mode 2 operation is

$$\frac{(2V_{in}/n) - (V_{in}/n)}{Z_0} \geq I_0 + nI_{Lm} \tag{14}$$

The selection of the auxiliary capacitor is given from two basic conditions given by equations (15) and (16).

$$C_a \geq \frac{L_L n^2 (I_0 + nI_{Lm})^2}{V_{in}^2} \tag{15}$$

$$C_a \leq \frac{4n^2 (1 - D)^2 T^2}{\pi^2 L_m} \tag{16}$$

4. PI CONTROLLED ZCS FORWARD CONVERTER

In this section the closed loop control of ZCS forward converter is given and Fig.14 shows the block diagram of the converter with PI controller.

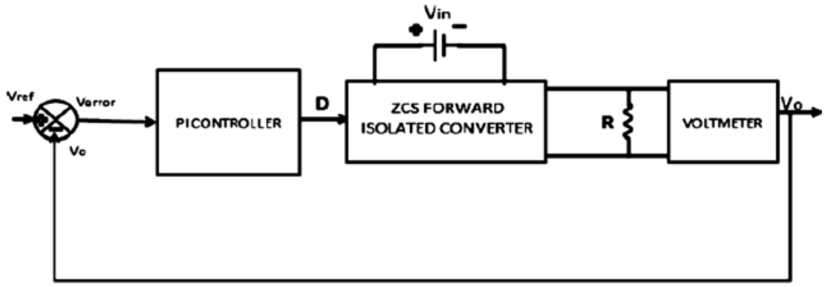


Fig. 14. Block diagram of PI controlled converter.

A proportional–integral controller is a generic control loop feedback mechanism widely used in industrial control systems. A PI controller calculates an "error" value as the difference between a measured process variable and a desired set point. The controller attempts to minimize the error by adjusting the process control inputs.

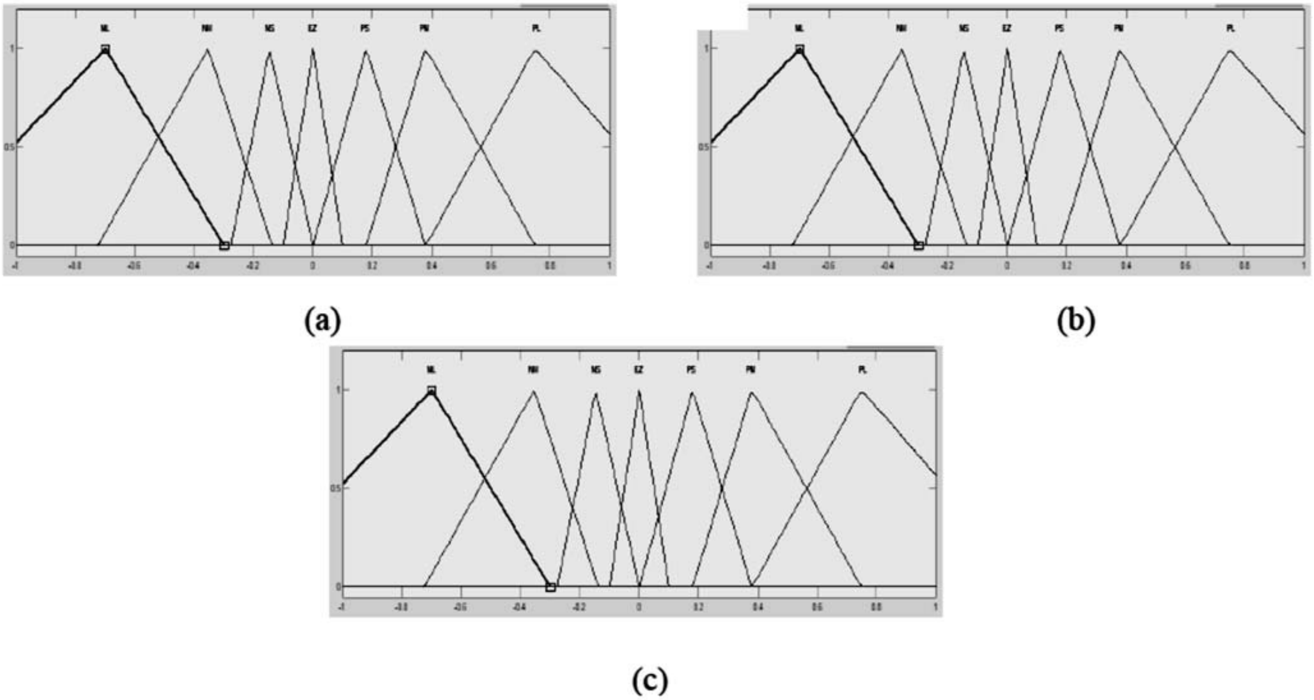
The proportional and integral terms are summed to calculate the output of the PI controller. Defining $u(t)$ as the controller output, the final form of the PI algorithm is

$$u(t) = \mathrm{K}_p e(t) + \mathrm{K}_i \int e(t)dt \tag{17}$$

Where, the error $e(t)$ is the difference between command and plant output, and it is the controller input; the control variable $u(t)$ is the controller output.

5. FUZZY LOGIC CONTROLLED ZCS FORWARD CONVERTER

The design of fuzzy logic controller involves three steps namely fuzzification, inference engine and defuzzification. The fuzzification of error, change in error and duty ratio is defined with seven linguistic variables as NL (Negative Large), NM (Negative Medium), NS (Negative Small), ZE (Zero), PS (Positive Small), PM (Positive Medium), and PL (Positive Large).



(a) (b)

(c)

Fig. 15. Membership functions for (*a*) error, (*b*) change in error and (*c*) control signal.

These fuzzified variables are processed through the inference engine where the set of rules is implied based on **and** (Min) operation and all these rules are aggregated based on **or (Max)** operation to get fuzzy output.

Table 2 shows the rule base made up of with if-then conditions if followed by antecedent and then followed by consequent. Antecedents are formed with error and change in error defined with linguistic terms connecting them by and connector. Thus the uncertainty associated with the description of heuristic knowledge is tackled by using fuzzy logic in the development of the heuristic IF-THEN rules. The hypothetic risk of problem associated with many inputs and one output can be solved by giving a degree to a membership functions (like small, medium & big). The centroid method is very popular, in which the center of mass of the result provides the crisp value.

Table 2. Rule Base for Fuzzy Logic Controller.

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

6. SIMULATION RESULTS

Fig.16 represents the Simulink diagram of the ZCS forward converter with simple auxiliary circuit used to reduce the Voltage from 150V to 32V with 200W output

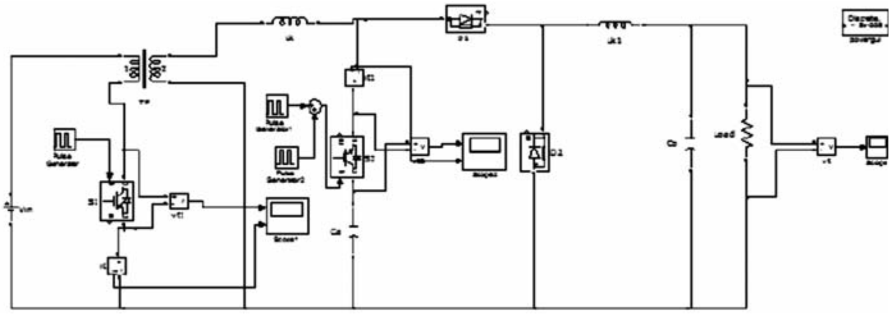


Fig. 16. Simulink model of ZCS forward converter with simple auxiliary circuit.

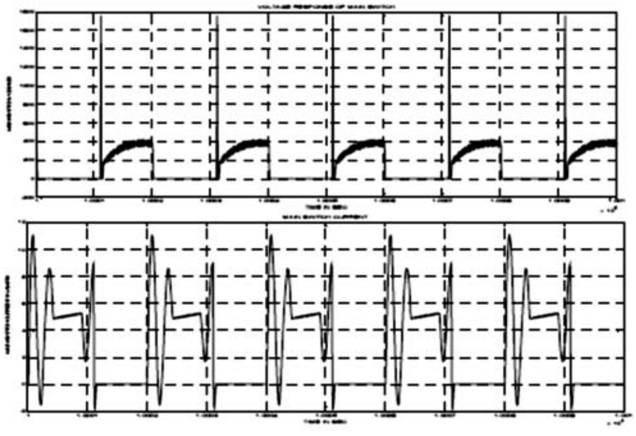


Fig. 17. Main switch voltage and current responses of ZCS forward converter.

Fig.17 shows the voltage and current waveforms of main switch, and from section II the Vs is $V_s = V_{in} + n^2 Z_1 \overline{I_{Lm}}$ gives 310V and the peak value of switch current as $(I_0/n) + (V_{in}/nZ_0)$ gives 10.99A

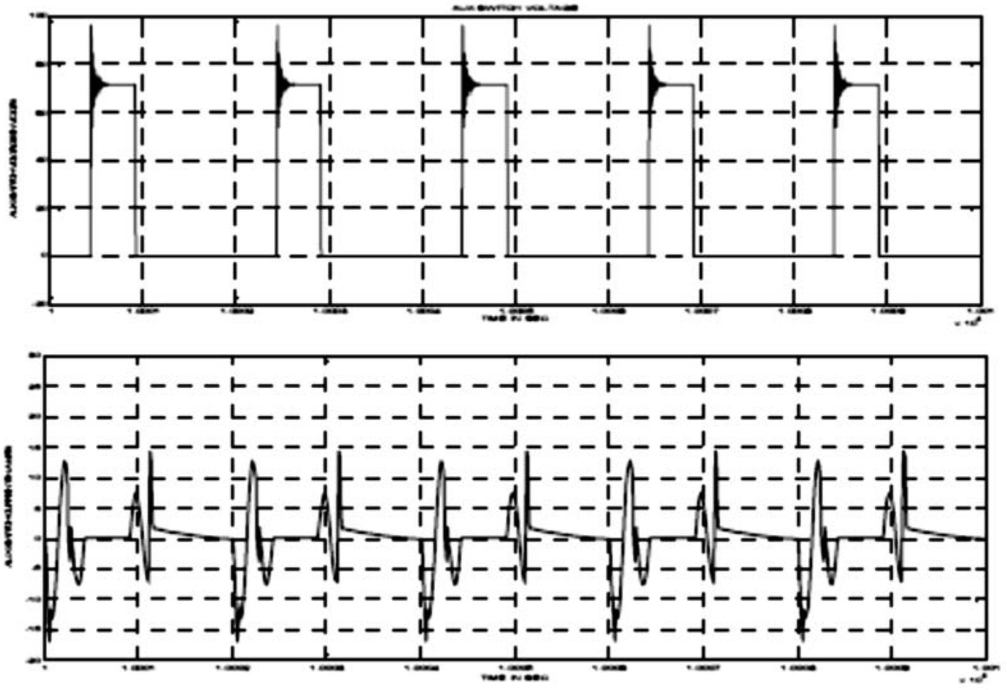


Fig. 18. Auxiliary switch voltage and current responses of ZCS forward converter.

Fig.18 shows the voltage and current waveforms of auxiliary switch and from section II the $V_{sa} = \frac{V_{in}}{n}$ gives 75V under steady state and the peak value of switch current as $I_0 + nI_{Lm}$ gives 6.925A.

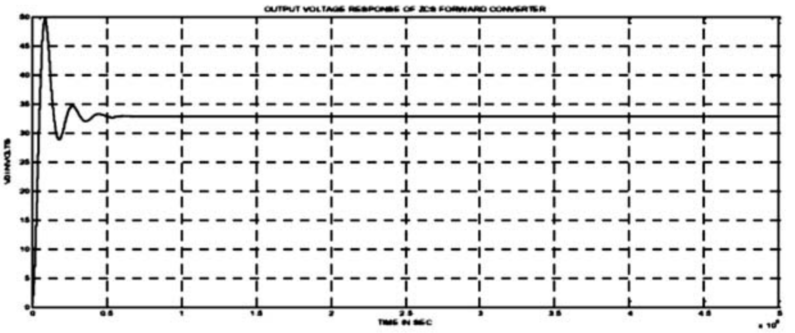


Fig. 19. Output voltage response of ZCS forward converter.

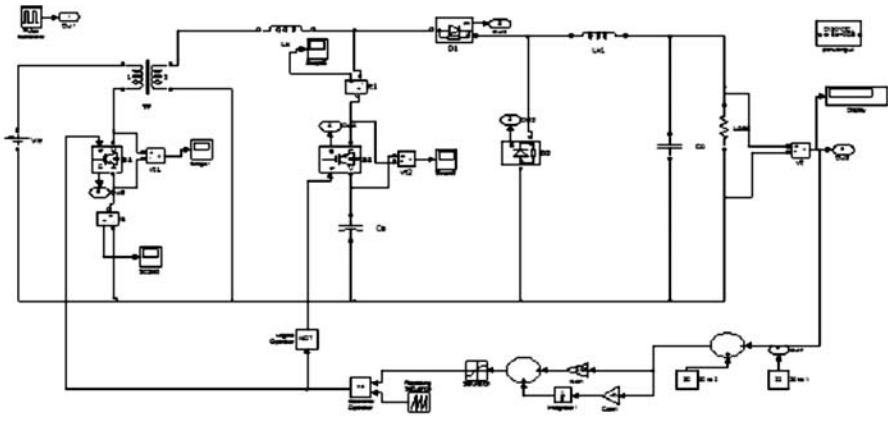


Fig. 20. Simulink model of PI controlled ZCS forward converter.

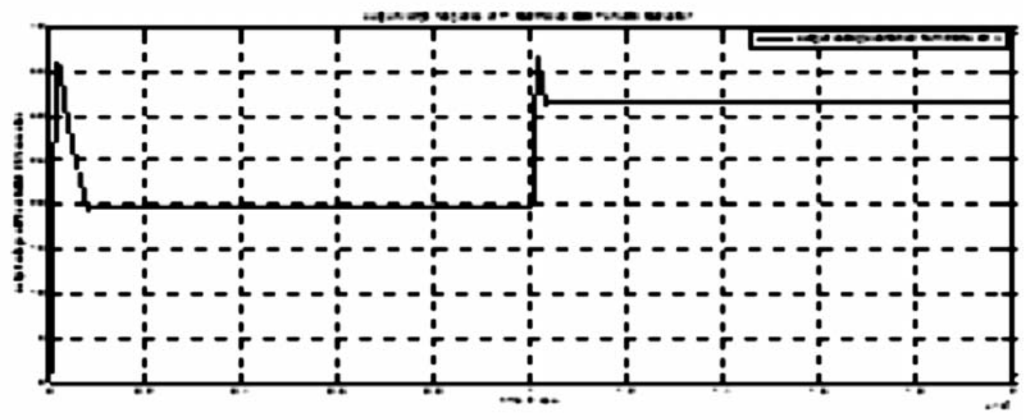


Fig. 21. Output voltage response of PI controlled ZCS forward converter.

Fig. 22 shows the output voltage step response of PI controlled ZCS forward converter controlled its voltage from 20V to 32V at a step time of 1µ sec.

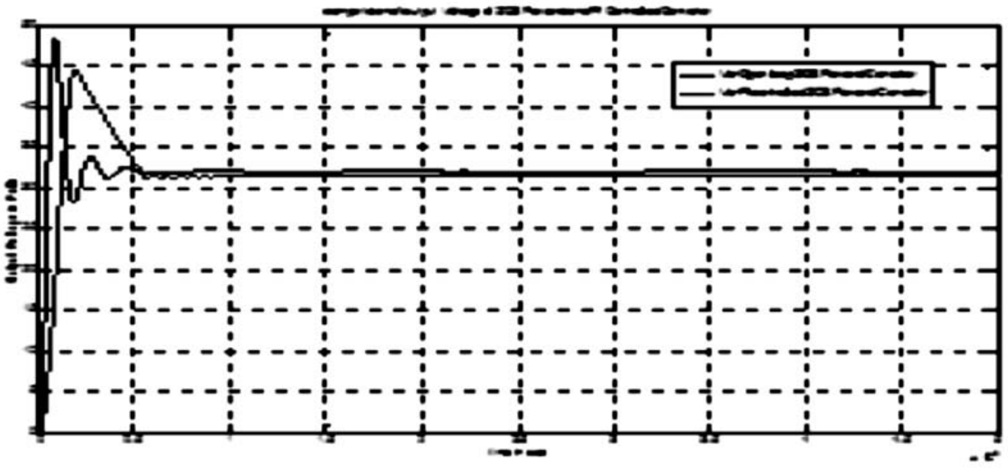


Fig. 22. Comparison of output voltage responses of ZCS and PI Controlled ZCS forward converters.

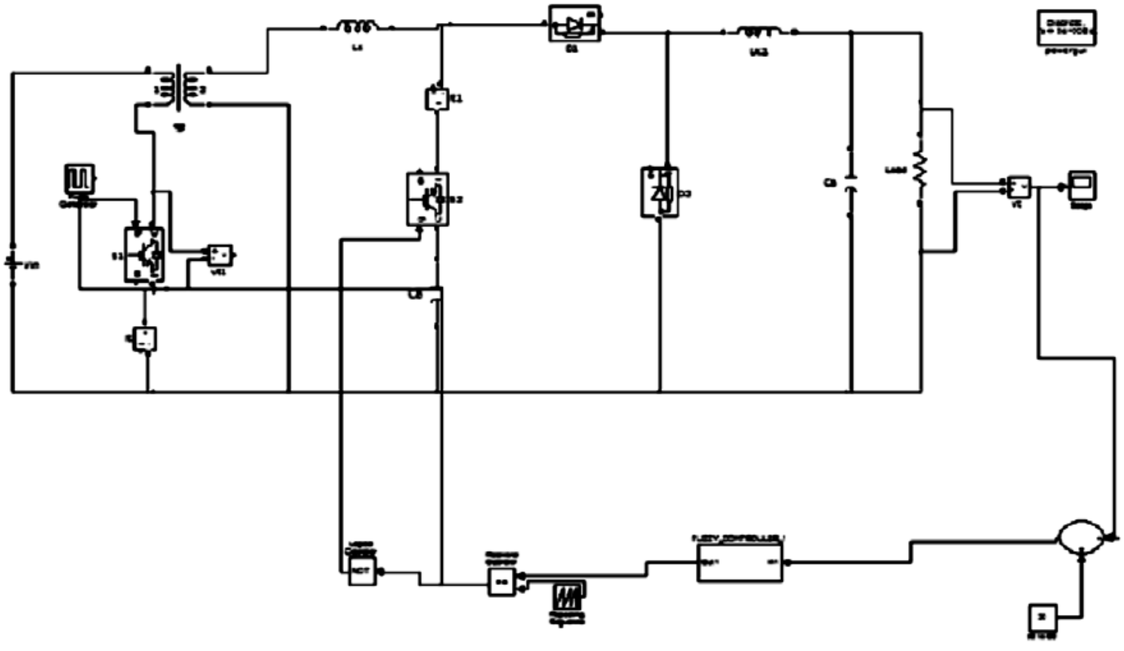


Fig. 23. Simulink model of fuzzy logic controlled ZCS forward converter.

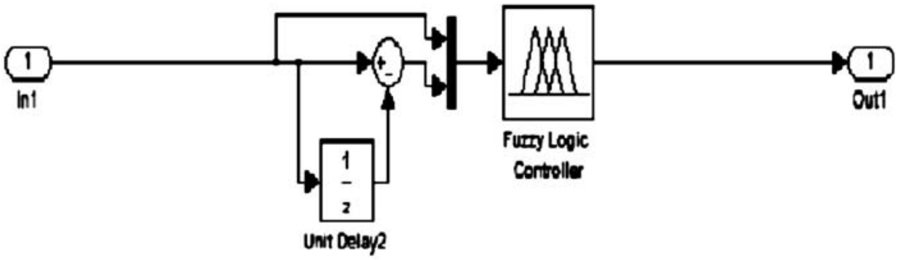


Fig. 24. Fuzzy logic controller for ZCS forward converter.

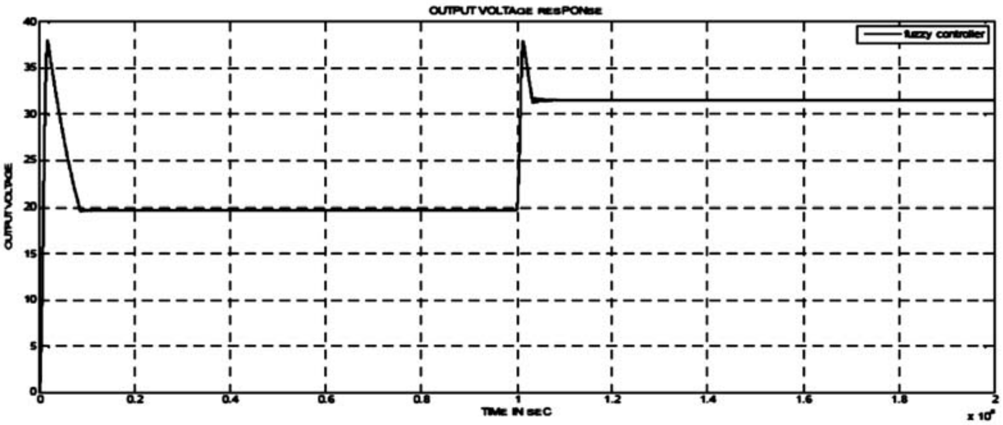


Fig. 25. Output voltage response of Fuzzy Logic Controlled ZCS forward converter.

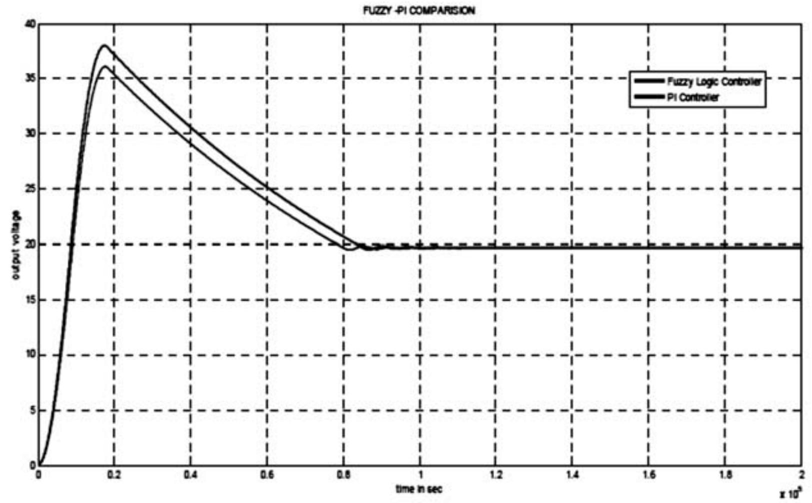


Fig. 26. Comparison of output voltage responses of PI Fuzzy Logic Controlled ZCS forward converters.

7. CONCLUSION

In this paper, the Forward converter is soft switched by ZCS technique using simple auxiliary circuit along with closed loop operation using the PI and fuzzy logic controller. All the devices in this converter are fully soft switched which improves its efficiency from 84 to 89% and this soft switching of ZCS operation is discussed in section II with a peak current of 10.99 A and 6.925 A for main and auxiliary switches respectively. The simulation analysis shows that the proposed converter doesn't require an additional inductor to reset the transformer core. Also the output voltage is controlled to a desired value effectively using intelligent controller when compared with the conventional PI controller. The fuzzy controller voltage response has comparatively less peak voltage of 36 V and that of with PI is 40V. Also the steady state performance is better in fuzzy in terms of zero steady state error and less steeling time etc. as shown in Fig.25

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