Implementation of ZCT PWM Converters for Renewable Energy Applications

Sankar.P[1], Jegatheesan.R[2]

Assistant professor, Dept. of EEE, CSI College of Engineering, The Nilgiris, Tamilnadu, India-643215

PG Student, Power Electronics & Drives, CSI College of Engineering, The Nilgiris, Tamilnadu, India-643215

ABSTRACT: In this paper an improved two types of ZCT PWM buck DC-DC Converter is proposed. Also a comparative analysis is structured between the conventional ZCS and the proposed ZCT PWM converters. The Conduction duty cycle is increased step by step for both the ZCS and ZCT PWM converters and respective results are tabulated for the power and loss comparison. The proposed converter generates reduced switching loss and increased efficiency than the conventional ZCS PWM converter. Additionally, a closed loop approach is also done for both the ZCS and ZCT PWM DC-DC converters using the PI controller design. All the simulation works are carried out under the MATLAB SIMULINK environment at a frequency rate of 10 kHz.

KEYWORDS: Buck, ZCS, ZCT, PWM, Switching loss, Efficiency.

I. INTRODUCTION

Soft switching techniques are used to overcome the problems of the hard switching DC-DC converters, the problems of the hard switching are, switching losses high, device stress and thermal management is high, high EMI due to the high di/dt and dv/dt and energy loss in stray inductance and capacitance. These problems can be overcome by using the snubber circuits to reduce the di/dt and dv/dt, circuit layout to reduce the stray inductance and capacitance, proper gate drive circuit, Soft switching techniques to achieve ZCS/ZVS. A snubber circuit reduces the switching losses and stresses, but increase the total power loss in the converter circuit. In soft switching, the switching transition occurs under favourable conditions. (i.e) the switch is turned on or turned off at zero crossings of the current or voltage. Whenever the frequency increases the speed of the operation also increases that induce the high current stress, voltage stress and power losses in normal hard switched converters, but in this soft switching converters the stress and losses reduced by including the resonant concept in the circuit along with the PWM technique. As a result of reduction in switching stress and switching loss leads to increase in the efficiency and power conversion capability. Resonant converters (RC) and Quasi resonant converters (QRC) are under the family of soft switched converters. By adding one tank circuit (LC) to the normal hard switched converters this RC and QRC can be derived. Here the resonant period controls the switch on and off time, since the resonant period mainly depends on the switching frequency, and so the converter output is also controlled by the same. Therefore the control is frequency control and not follows the PWM control techniques. In order to improve the control and performance the ZVT and ZCT has been developed.

S.Nigam, P.Baul, S.Kumar [1] have discussed about the new ZVT buck topology that uses the shunt resonant branch to achieve the soft switching without increasing the stress of the active switch. The proposed topology compared with the conventional ZVS and generated the better results in terms of reduced switching loss and improved efficiency.G. Hua, E. X. Yang, Y. Jiang, and F. C. Lee [2] discussed a new hard switching auxiliary circuit based ZCT PWM converter that resulted better than the normal hard switched buck converter, with the efficiency of 97%. Under light loads the auxiliary switch of the proposed converter handles less circulating energy but for the high loads the turn off losses increased. Bodur, A.F Bakan [3] have proposed an improved snubber cell based ZCT PWM buck converter for high power and frequency applications with 98% of efficiency under light load conditions. Milan M. jovanovic [4] discussed about the existing resonant, quasi-resonant, multi-resonant and soft switching PWM techniques - merits and limitations. P. Das and G. Moschopoulos proposed a new ZCT PWM boost converter with reduced auxiliary circuit losses [5, 6] uses the coupled transformer to transform the energy from the input to the output side. Less efficient in light load condition and transformer reduces the circulating energy of auxiliary circuit in higher loads is compared with all other ZCT PWM techniques. E.Adib and H.Farzanehfard proposed [7] a family of PWM converters, the two switches operates under out of phase and shares the output current while achieving the soft switching. The circuit is established for all the topologies. M. Prathap Raju, A. Jaya Lakshmi [8] presented the

all the topologies of the soft switching new ZCT PWM converters and compared the switching loss and stress with the hard switched converters. The proposed ZCT converters produced better results than hard switched converters.

In these converters, the resonance is limited only during the switching instances, so these converters operate like a regular PWM converters. In these converters an auxiliary circuit is connected via an auxiliary switch that provides the soft switching conditions at the switching instances. In ZVT and ZCT the auxiliary circuit consist of an auxiliary switch and resonant elements that provides the soft switching transition. In ZCT converters, by turning the auxiliary switch on, the main switch current is reduced to zero for the switch turn off. In ZVT converter by adding a capacitor parallel to the switch provides the soft switching turn off, and in ZCT a series inductor provides the soft switching turn on. This paper provides the simulation analysis of two improved ZCT buck PWM converters, the switching loss & efficiency is calculated for the proposed ZCT converters and is compared with of the conventional ZCS PWM buck converter switching loss & efficiency. All the simulation works are carried out on the MATLAB simulink at 10 kHz.

II. PROPOSED ZCT PWM CONVERTERS

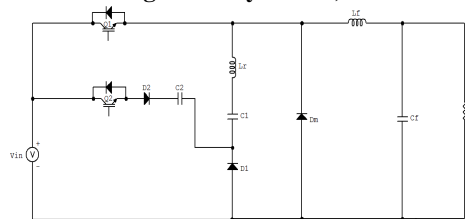### 2.1 Type I (Converter with hard switching auxiliary circuit)

Fig. 1 ZCT type I circuit Diagram

The proposed ZCT buck converter with hard switching auxiliary circuit is shown in figure 1 and the The circuit consists of main switch Q1, auxiliary switch Q2, diodes D1, D2, and Dm, capacitors C1, C2, and Cf. Initially assumed that the main switch is in conducting state. The D2, C2 in series with the switch Q2 reduces the negative peak current stress during the operation of the ZC switch operation of Q2.The converter output side looks like the normal hard switched buck converter. Lf, Cf is the filter inductor and filter capacitor in the output side. Lr, C1 is the resonant inductor and capacitor that filters out the ripples and commutating the switch after the achievement of resonance. This type of converter is more appropriate for the lower kW power applications. The input current is splits in to two branches for the Q1 and Q2 switches

2.2 Type II (converter with soft switching auxiliary circuit)
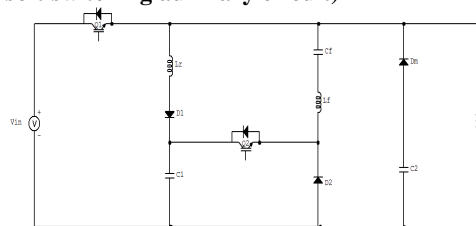

Fig. 2 ZCT type II circuit diagram

Figure 2 shows the circuit diagram of the ZCT PWM converter with the soft switching auxiliary circuit. The circuit consists of two switches. The main switch Q1, auxiliary switch Q2, the filter inductor Lf, filter capacitor Cf, resonance inductor Lr, diodes D1, D2, Dm and capacitors C1, C2. Before the first interval the capacitor Cf is assumed with the charge level of 2Vin, in this converter the Lr, C1 and Lf, Cf forms the resonant circuit. This converter has the adoptable rating for medium and high power kW applications. The full input current is flowing initially through the switch Q1 then through the auxiliary switch Q2.This type converter more exactly produces the power according to the requirement, handles less circulating energy than the hard switched converters.

III. SIMULATION VERIFICATION IN OPEN LOOP

The open loop and closed loop operations of ZCS and ZCT topologies are explained in MATLAB SIMULINK simulation environment.

3.1 Simulation of Conventional ZCS PWM Converter in Open Loop

Fig 3 shows the simulation circuit diagram of ZCS PWM converter, which is simulated in the MATLAB simulink at 10 kHz frequency for the 60% conduction cycle. In Fig 3 the inductor Lr and Cr forms the resonance; their values are calculated in basis of the resonant concept. Filter inductor Lf, filter capacitor Cf is adjusted to produce the reasonable output result with respect to the duty ratio. The Lr, Cr can be calculated by the formula

$$\omega = \frac{1}{\sqrt{L_r C_r}}$$

$\omega=2\pi f$; f=10 kHz; let L_r=50µH and C_r=5.06µF, L_f=30µH, C_f=9µF and R=5Ω.Fig 4 shows the gate pulse of the Q1 switch and the overlap between the switch current and voltage. The voltage across the switch reaches zero and then the current starts to increasing, but some voltage spikes appears across the primary switch Q1. This indicates some amount of stress appears on the switch that leads to the losses. Fig 5 shows the output voltage and output current. The output voltage for the buck converter Vout=DVin; D=T_{on}/T. Output voltage closely reaches the expected value, but with the few amount of distortion initially. Fig 6 shows the switch voltage and switch current. Switch voltage reaches to high amount of stress, respectively the current also containing a sudden increase from its average value. The switch voltage has the more maximum than the switch current.
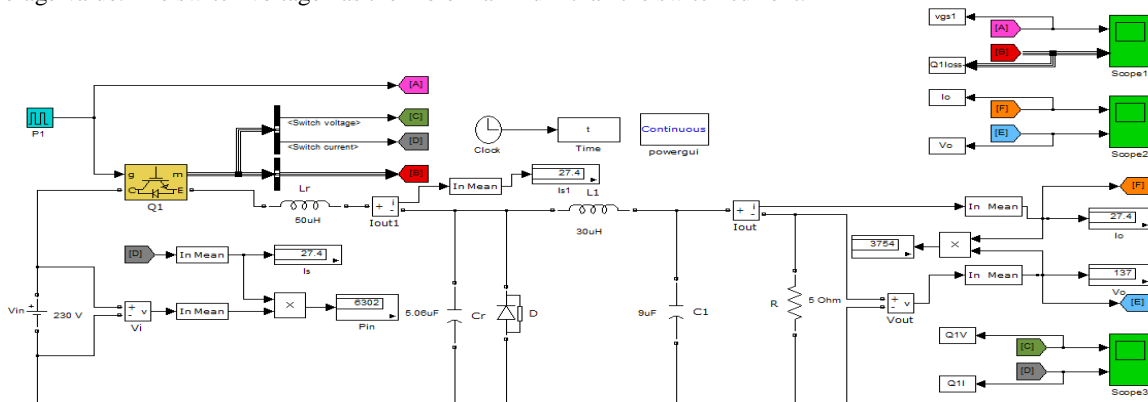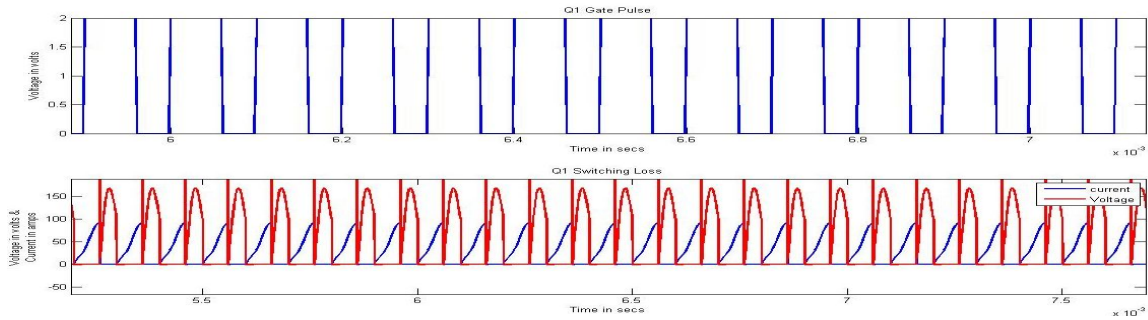

Fig. 3 Conventional ZCS PWM Buck Converter

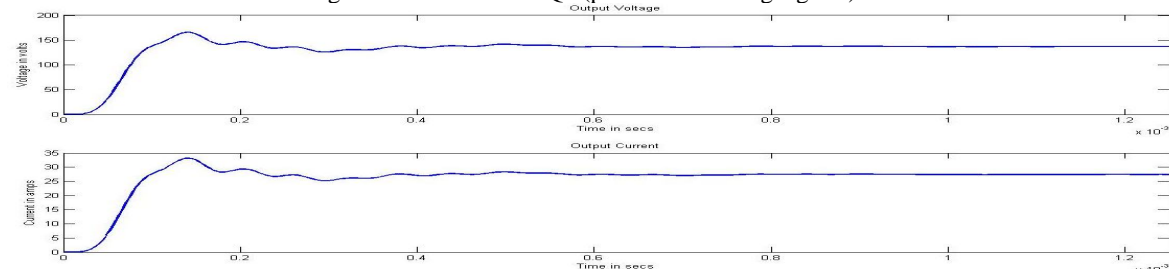Fig. 4 ZCS PWM buck Q1 (pulse & switching signals)

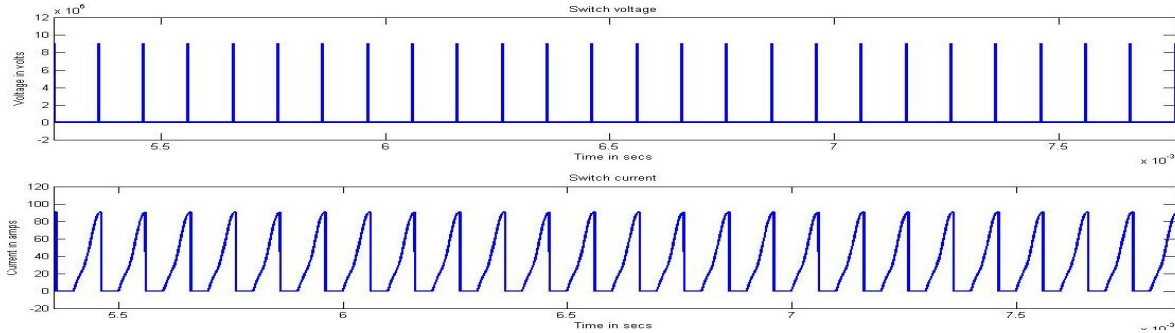Fig. 5 ZCS PWM buck output (voltage & current)

Fig. 6 ZCS PWM buck Q1 (Voltage & current)

3.2. (Type I) ZCT PWM Converter with Hard Switching Auxiliary Circuit in Open Loop Simulation

Fig 7 shows the the one of the types of MATLAB simulated circuit of the proposed new ZCT PWM converter with hard switching model auxiliary circuit. The ZCT achieved by the adding additional switch Q2, that is parallel to the main switch Q1.this auxiliary switch Q2 does not have the capability of transfer the power from input to the output. The auxiliary switch Q2 and the components present in the circuit also operate under ZCS to minimize the losses and stresses. Compare to the conventional ZCS converter it consists reduced turn off time, implies reduced stress and loss and improved efficiency. The Inductor Lr and C1 form the resonance. Similarly Lf and Cf forms the resonance. The converter contains of some additional components than ZVS PWM converter to reduce the switching loss and stress. This ZCT converter achieves closely to our power requirement under the light load conditions
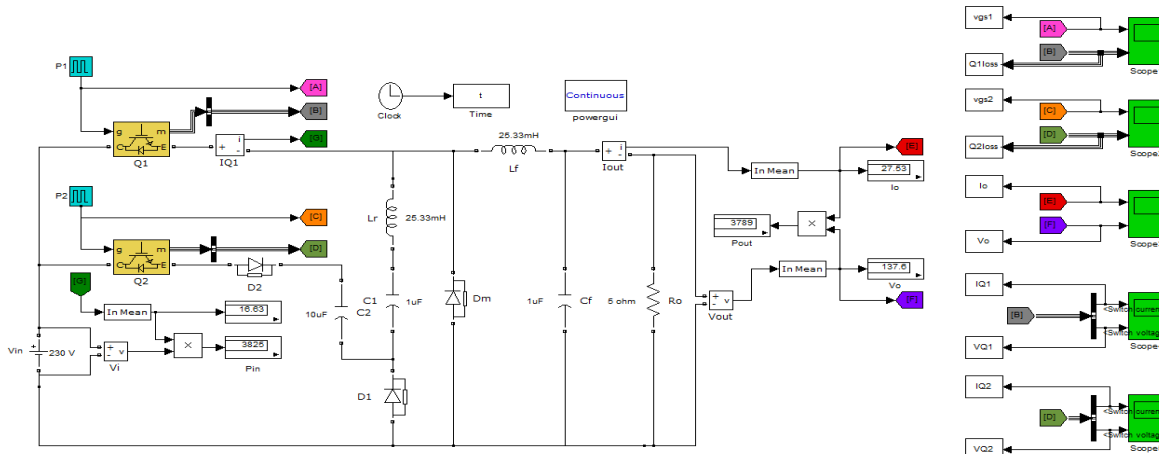

Fig.7 ZCT PWM Buck Converter with Hard Switching Auxiliary Circuit

$$\omega = \frac{1}{\sqrt{L_r C_1}}$$ Lr=Lf=25.33mH; C1=Cf=1µF. C2=10µF Ro=5Ω.f=10 kHz

Fig 8 shows the type I ZCT PWM buck converter Q1 gate pulse and the switching signals of Q1.the switching signals containing switch voltage and switch current. It shows clearly that the main switch operates under ZCS condition without having any losses in it. Exactly the current reaches zero when the switch voltage present and vice versa. But this is not in the case of conventional ZVS PWM converter. This property of ZCT converter leads to efficiency improvement and reduced loss, stress achievement.
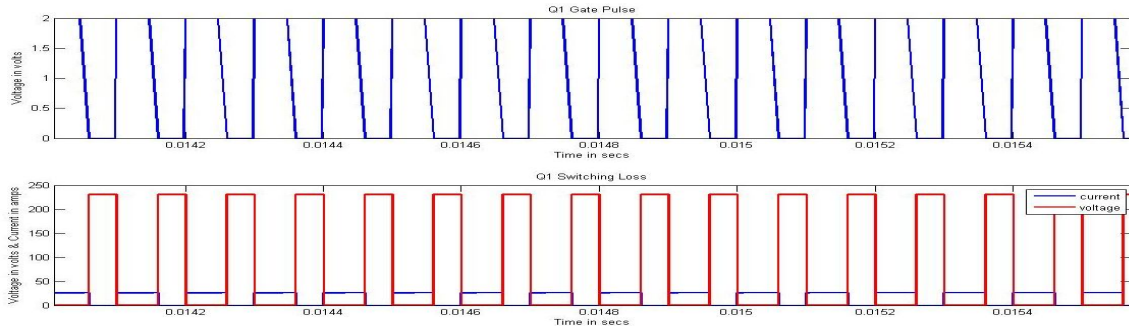
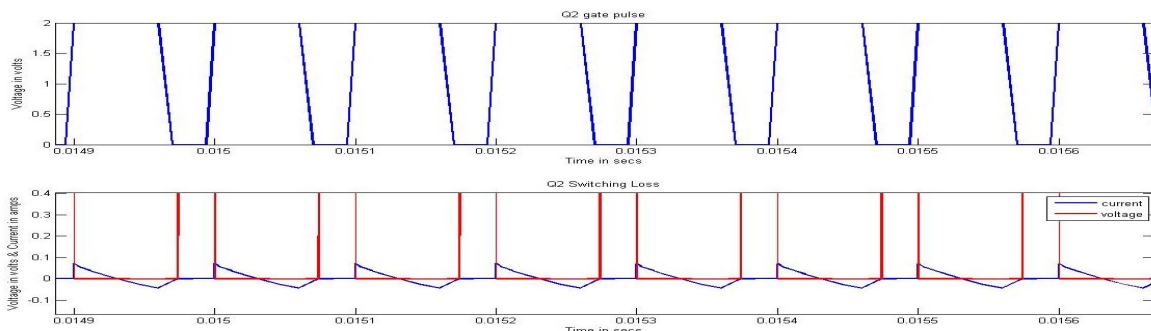Fig. 8 ZCT1 PWM buck Q1 (gate pulse & switching signals)

Fig.9 ZCT1 PWM buck Q2 (gate pulse & switching signals)

Fig 9 shows the auxiliary switch Q2 gate pulse and its switching sequence. The Q2 switch also operates under the ZCS condition, but having some minor losses in it, due to the circulating energy handling capability. It will not transfer the energy to the load side; it will operate only during the attainment of the resonance condition. The switch current produces much lower value compare to the switch voltage. Switch current has certain negative flow of current that leads to the minor loss of Q2 due to the presence of buck diodes. So it clearly indicates the auxiliary switch is activated during the resonance condition, after achieving this condition this switch gets turned off, (i.e) the switch Q2 does not have capacity to transfer the power from input to the output side. Fig 10 shows the output voltage and output current of the type I ZCT PWM buck converter. This type I converter produces the exact output voltage and current levels, what the buck converter needs depending on the duty ratio relationship. For the 0.6% of duty cycle it produces 137.7 volts output voltage, provided that Vin=230 volts (0.6*230=138 volts) but not in the case of ZVS converters. Fig 11 and Fig 12 shows the switch voltage and switch current plots of the Q1 and Q2 switch. Q2 switch has been given with more turn on period than Q1, to achieve ZCS condition. This individual plots describes the clear view of the ZCS conditions of these switches. When the voltage available across the switch, implies the open circuit, so there is no flow of the current, therefore switch current value is zero and some amount of switch voltage will be present across the switch. Thus the 2 switches operate under the ZCS conditions.
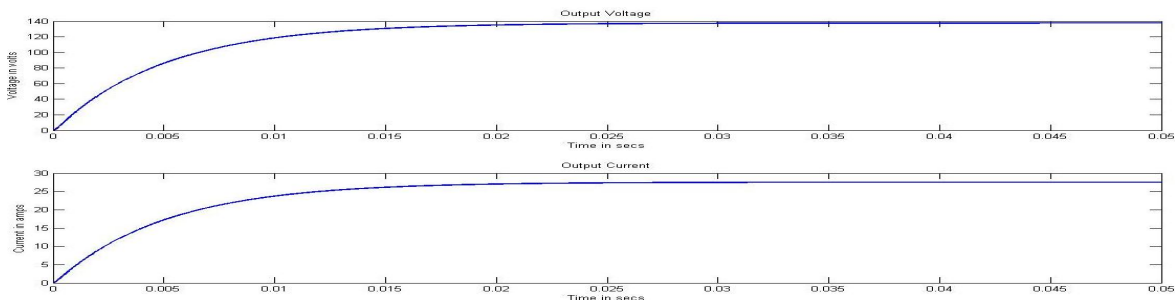

Fig. 10 ZCT1 PWM buck output (voltage & current)

3.3. (TypeII) ZCT PWM Converter with Soft Switching   Auxiliary Circuit in Open Loop Simulation

Fig 13 shows the type II ZCT PWM buck converter with soft switching auxiliary circuit simulated in MATLAB at 10 kHz frequency. The output filter side in the fig 13 shows clearly that it is not similar with the normal hard switched buck converter. The two switches Q1 and Q2 are reducing the stress and losses. Q1 is the main switch and Q2 is the auxiliary switch. Q2 switch is added to the circuit to share the stress of the Q1 switch, and this switch also operates under ZCS condition like Q1 switch. Here Lr, C1 and Lf, Cf forms the resonant conditions. Lr=Lf=25.33mH, C1=Cf=1μF, c2=1nF, Ro=5Ω and f=10 KHz.
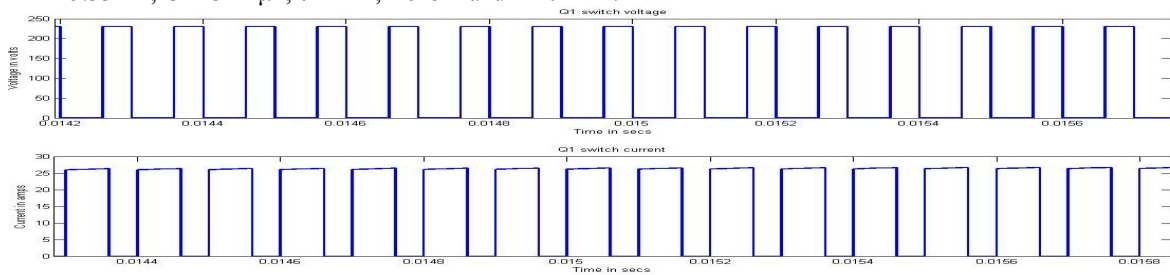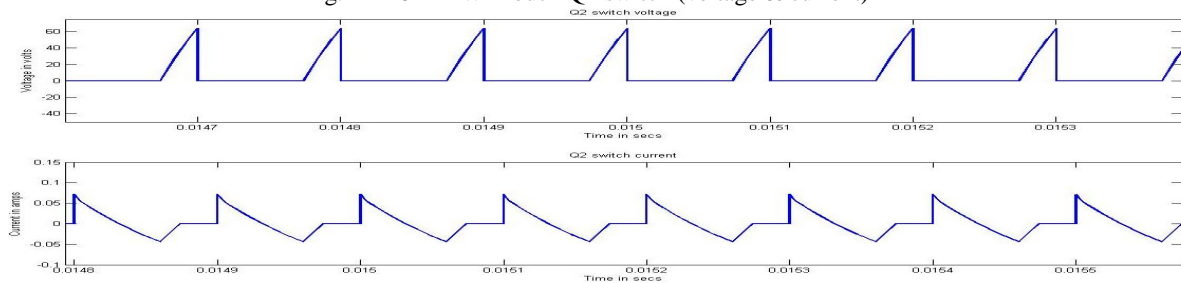

Fig. 11 ZCT1 PWM buck Q1 switch (voltage & current)

Fig. 12 ZCT1 PWM buck Q2 switch (voltage & current)

Fig 14 shows the switch Q1 gate pulse and switching sequence of the type II ZCT PWM buck converter with soft switching auxiliary circuit. The Q1 switch operates under the ZCS condition. That is the switch current reaches to zero then only the switch voltage starts to increase. Thus the alternate reaching of switch voltage and switch current to zero reduces the switching loss and stress of the converters, it reduces the overlapping time periods of the switch voltage and current. Fig 15 shows the Q2 gate pulse and switching sequence. Generally the Q2 auxiliary switch contains more conduction time than the main switch Q1 to share the stress and to achieve the resonance conditions. After attaining the condition of resonance the switch Q2 is turned off. The minimal current in the switch Q2, goes negatively to reach zero to achieve ZCS condition always contains some minimal amount of circulating energy due to incapable of power transfer, but reduced amount than the type I ZCT and conventional ZVS PWM converters.

Fig 16 shows the output voltage and current of the proposed converter. The output voltage and current reaches the exact value, what the actual buck converter needs. In this simulation a conduction period of D=0.6, Vin=230 volts. For buck converter Vout=D*Vin (0.6*230=138 volts).the proposed converter also produces the same required amount of voltage and current, with very minimal level of distortion. In this type of converters, the required level of power could be achieved with 99% of efficiency but not in previous proposed converters. The switch Q1 and Q2 handles less amount of circulating energy to success the power level requirement.
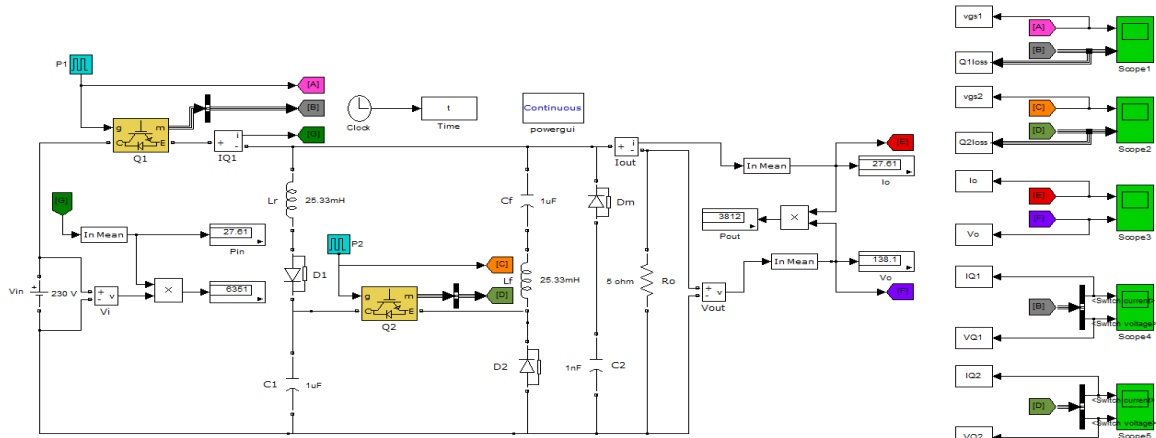
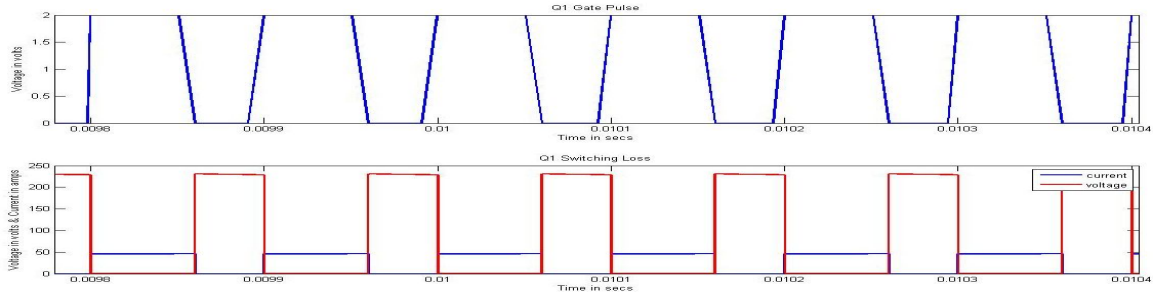Fig.13 ZCT2 PWM Buck Converter with Soft Switching Auxiliary Circuit

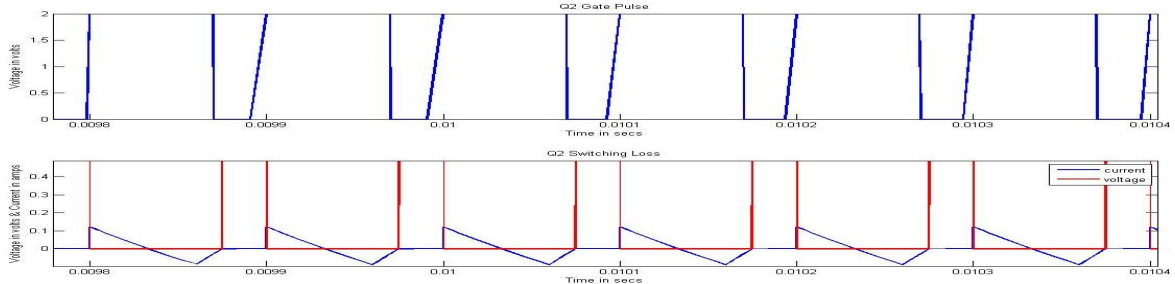Fig. 14 ZCT2 PWM buck Q1 (gate pulse & switching signals)

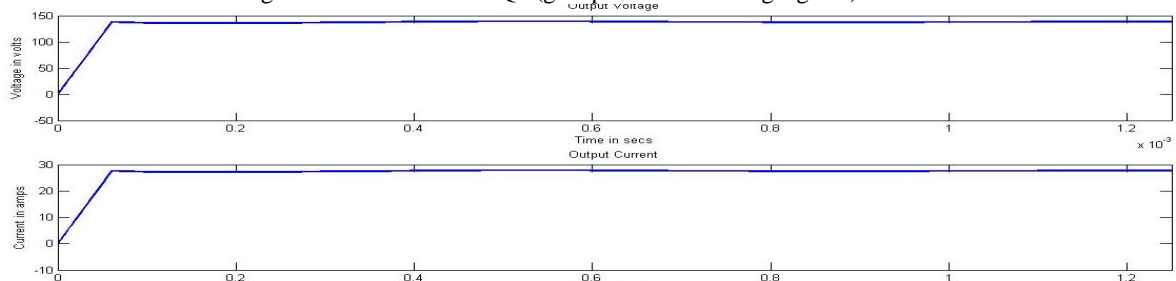Fig.15 ZCT2 PWM buck Q2 (gate pulse & switching signals)

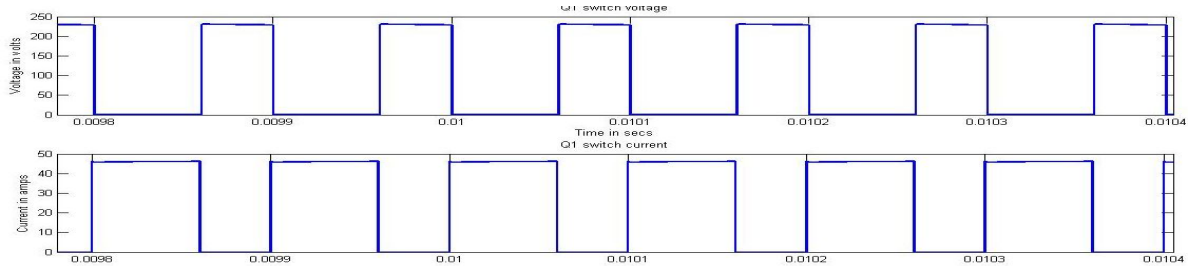Fig. 16 ZCT2 PWM buck output (voltage & current)

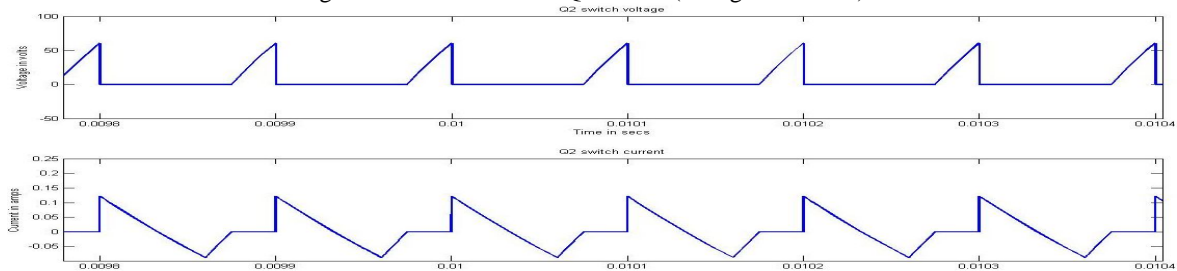Fig. 17 ZCT2 PWM buck Q1 switch (voltage & current)

Fig. 18 ZCT2 PWM buck Q2 switch (voltage & current)

IV. SWITCHING LOSS CALCULATION

The average switching power loss for any controllable switch Psw can be approximated to

$$P_{sw} = 1/2\ V_{in} I_{out}\ f\ t_f$$

V_{in} = Input voltage applied
I_{out} = Output load current
f = Switching frequency
t_f = Falling time = $(t_{on} + t_{off})$
t_{on} = On time duration of IGBT
t_{off} = Off time duration of IGBT

Switching loss has been calculated for the conventional ZCS PWM converter, ZCT PWM converter with hard switching auxiliary circuit and for ZCT PWM converter with soft switching auxiliary circuit, in MATLAB simulink open loop simulation results. The falling time t_f decides the losses in the converter.

Fig. 19 1 cycle of ZCS buck   Fig. 20 1cycle of type I ZCT buck   Fig. 21 1 cycle of type II ZCT buck

For the conventional ZCS PWM buck converter the falling time can be calculated from the switching signal of the primary switch Q1 from the fig 4, when expanding a single cycle of switch current and switch voltage, the t_f can be approximated. From the fig 19 the ZCS t_f can be calculated by expanding the cycles more and here getting the 0.6μs as the total falling time. It will be detected by disabling the zero crossing detection in the MATLAB simulink simulation properties, so the overlap time period will be known exactly between switch voltage and switch current. Similarly for the type I ZCT PWM converter the turn off time can be calculated from the fig 20, the falling time for type I ZCT PWM converter with hard switching auxiliary circuit is 0.35μs. The type II ZCT PWM converter with soft switching auxiliary circuit follows 0.25 μs as the falling time. Fig 21 shows the switching current and switching voltage combinations of the type II ZCT PWM converter. From the fig 19, 20 and 21, it is somewhat clear that the ZCS PWM converter having some high stress and loss than the proposed ZCT PWM converters.
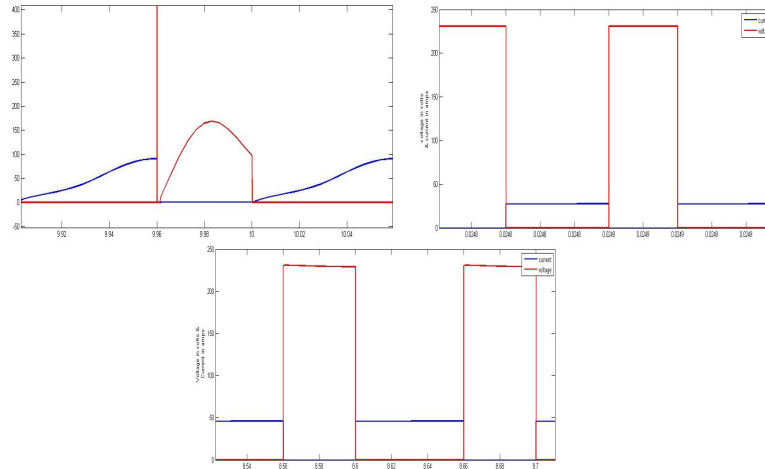
Table I shows the resultant values of the conventional ZCS PWM buck converter, simulated in the MATLAB simulink for the different pulse width duty cycles. Duty cycle D is equals to Ton/T. Ton is the conduction period of the switch and T is the total time period. For the buck converter output voltage Vout is given as Vout=D*Vin; for the different duty cycles the output voltage can be formulated. From the table I can be noted that the input current equals to the output current from 30 to 90 duty cycles range. For 10% of duty cycle Vout=0.1*230=23 volts is expected, but the output is only about 12.26 volts produced as the result, efficiency is projected about 10% but only 5.78% attained. For 20% duty cycle the output voltage (44.77) is closer to expected voltage (46) so it closer to the efficiency of 20%.The duty cycles 30%, 40% and 50% are producing more output voltage than the actual expected output voltage. So the efficiency also crosses the limit from its actual limit. The losses can be accepted, the increased power limit will damage our device. Duty cycles 60%, 70% and 80% more or less produce the results what the converter actually needed, so the efficiency level also comes closer to the safer margin level. The conventional ZCS buck converter is operating under the ZCS conditions, but it could not propose the exact result. Over the entire converter is producing only about 50% to 70% efficiency. Under the light load conditions these converters are more suitable with some amount of losses, but completely not for heavy loads.

Table II shows the resultant values of the ZCT PWM buck converter with hard switching auxiliary circuit for the different duty ratios. From the table, it can be noticed that the input current is different from the output current value, because of it is based on hard switching converter and the current here is branched for the Q1 and Q2 switches. Q2 switch current much less than the Q1 switch current. So the input power generated here is less, but the converter produces closer results that needed for a good converter circuit. It combines both the benefits of the hard switching and the soft switching converters. Therefore it produces the efficiency for each duty cycle closer the centum level than ZVS converters. The output voltage is much near to the anticipated voltage levels, only a deviation about 0.2 to 0.5 voltage levels. This converter has the reduced falling time than the conventional ZCS buck converter. As a result it contains compact level of switching losses and stresses than previously proposed ZVS converter. This converter produces the overall efficiency about 97.5%. The auxiliary circuit handles less energy than any other auxiliary circuits of other converters. The auxiliary switch has significant turn off losses that has greater effect on heavier loads, more circulating energy on Q2 switch but significantly less than the conventional ZVS PWM converter.

Table III shows the consequential values of the ZCT PWM buck converter with soft switching auxiliary circuit for the different duty ratio levels. This converter has overall better performance than the previous two converters. The input current and the output currents are same in this type of converters. Because the full input current is handled only by the Q1 switch during the initial levels. The output voltage is exact with the input voltage according to the buck converters ratio. For each and every duty cycles the voltage produced by this ZCT PWM converter satisfies the buck converters relation Vout=D*Vin. Even the output power also satisfies the condition Pout=D*Pin. The falling time of this converter is much less than the previous 2 converters. So the switching loss is more reduced than other two converters.

A.ZCS PWM BUCK CONVERTER PARAMETERS
TABLE I
ZCS PWM Buck Parameters
$V_{in}=230V$, $t_f=0.6\mu s$, $f=10$ kHz, $P_{sw}=1/2\ V_{in}\ I_{out}\ f\ t_f$

D (%)	Iin (A)	Pin (W)	Vout (V)	Iout (A)	Pout (W)	η (%)	Psw (W)
10	2.259	520	12.26	2.452	30.06	5.78	1.69
20	8.50	1955	44.77	8.954	400.8	20.50	6.17
30	16.21	3728	81.06	16.21	1314	35.24	11.18
40	21.43	4929	107.2	21.43	2297	46.60	14.78
50	24.36	5602	121.8	24.36	2966	52.94	16.80
60	27.40	6302	137.0	27.4	3754	59.56	18.90
70	32.06	7373	160.3	32.06	5138	69.68	22.12
80	36.83	8471	184.2	36.83	6783	80.07	25.41
90	39.23	9023	196.1	39.23	7695	85.28	27.06

.
B. ZCT PWM BUCK CONVERTER WITH HARD SWITCHING AUXILIARY CIRCUIT PARAMETERS
TABLE II
ZCT PWM Buck with Hard Switching Auxiliary Circuit Parameters
$V_{in}=230V$, $t_f=0.35\mu s$, $f=10$ kHz, $P_{sw}=1/2\ V_{in}\ I_{out}\ f\ t_f$

D (%)	Iin (A)	Pin (W)	Vout (V)	Iout (A)	Pout (W)	η (%)	Psw (W)
10	0.489	112.6	22.28	4.456	99.24	88.13	1.70
20	1.891	434.9	45.35	9.072	411.3	94.57	3.650
30	4.206	967.5	68.43	13.69	936.4	96.78	5.510
40	7.435	1710	91.50	18.30	1675	97.95	7.365
50	11.58	2663	114.6	22.92	2626	98.61	9.225
60	16.63	3826	137.7	27.53	3790	99.05	11.080
70	22.06	5198	160.7	32.15	5167	99.40	12.940
80	29.48	6781	183.8	36.76	6757	99.64	14.796
90	37.28	8574	206.9	41.38	8560	99.83	16.656

C. ZCT PWM BUCK CONVERTER WITH SOFT SWITCHING AUXILIARY CIRCUIT PARAMETERS
TABLE III
ZCT PWM Buck with Soft Switching Auxiliary Circuit Parameters
$V_{in}=230V$, $t_f=0.25\mu s$, $f=10$ kHz, $P_{sw}=1/2\ V_{in}\ I_{out}\ f\ t_f$

D (%)	Iin (A)	Pin (W)	Vout (V)	Iout (A)	Pout (W)	η (%)	Psw (W)
10	4.605	1059	23.02	4.605	105.9	10	1.323
20	9.206	2117	46.02	9.206	423.7	20	2.646
30	13.81	3176	69.04	13.81	953.3	30	3.970
40	18.41	4234	92.04	18.41	1694	40	5.292
50	23.01	5292	115	23.01	2647	50	6.615
60	27.61	6350	138	27.61	3811	60	7.937
70	32.20	7407	161	32.20	5185	70	9.257
80	36.80	8464	184	36.80	6771	80	10.58
90	41.40	9521	207	41.40	8568	90	11.90

V. SIMULATION VERIFICATION IN CLOSED LOOP
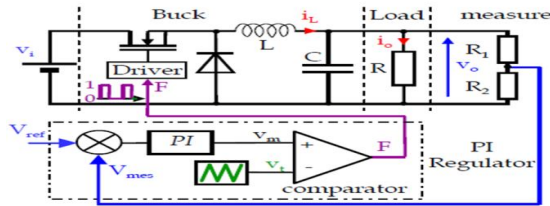

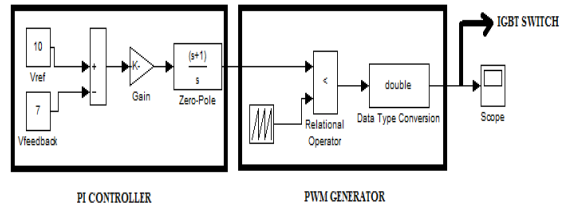Fig.22 Schematic of closed loop control   Fig. 23 Simulink structure of PI controller & PWM generator

In closed loop the part of the output signal is compared with a reference signal in the comparator, the error signal produced by the comparator is amplified by any controllers and driver circuit generates the pulses according to the error signal. Fig 24 shows the schematic of a closed loop controller. The closed loop controller is designed with the PI controller for the ZCS and ZCT PWM converters in the MATLAB simulink. For PI controller the transfer function is given as $PI=Kp+Ki/S= (Ki+KpS)/S=Ki ((1+S (Kp/Ki)/S)$. Kp-Proportionality constant, Ki-Integral constant. The PI controller turn out the error amplified signal and the PWM generator makes gate pulse signal for the switch to cause the required result. The simulink structure shows the PI controller and PWM driver Circuit in fig 23. This structure is adopted for the ZCS and ZCT PWM converters in MATLAB simulink for the closed loop operations. PI controller block is made as subsystem 1 and PWM block is subsystem 2.the gain is adjusted and in zero pole structure the Kp and Ki values are adjusted for the exact result. The pulse generated at the output side of the PWM block is given to the Q1 and Q2 IGBT switches. For the ZCS condition IGBT switch is more applicable due to the tail current turn off property that is it has more turn off losses at removal of gate pulse.

5.1. Conventional ZCS PWM Buck Converter in Closed Loop Simulation

Closed loop simulink structure of conventional ZCS buck converter is shown in fig 24. In simulation the reference voltage is fixed in a value of 100 volts, and input voltage is 230 volts. The gate pulses are generated automatically at the PWM simulink structure that is given to the switches Q1 and Q2, to achieve the exact reference voltage result. The output voltage and current waveforms shown in fig 25 and in fig 26 the gate pulse & switching signals are shown.ZCS PWM converter in closed loop exactly produces the output voltage with respect to the reference voltage setting the simulation diagram shown in fig 24. The output voltage and output current results are shown in fig 25, though it produces the response like a PI controller in closed loop it contains some distortions, it consist some oscillations in its output waveforms, the poor design of a closed loop controller may be a reason for it. The power level incapability is the main reason because only a single switch is presenting here, so the stress of the switch is more that is replied as oscillations in the output voltage and current, it may forms the heat and reason to failure of the switching devices. The fig 26 shows the gate pulse and switching sequences of current and voltage. The converter has high circulating current, stress problem in the switch Q1. It replies with some losses as the output for the specified reference voltage, some level of sudden voltage spikes appears in the switch Q1 that may cause the severe stress on the switch and a sudden failure for the switch. The switch current follows the switch voltage with exact attainment of the ZCS condition with stress and temperature problem, but this problem fairly cleared in ZCT PWM converters.

5.2. ZCT PWM Converter with Hard Switching Auxiliary Circuit in Closed Loop Simulation

Closed loop simulation circuit of the ZCT PWM converter with hard switching auxiliary circuit shown in fig 27. This converter more exactly produces the output voltage as equal to the reference voltage and PI controller response, with minimum level of distortions. Fig 28 shows the simulation results of the output voltage and output current. The reference voltage is fixed about 100 volts. The result of the voltage value is also 100 volts, shows the converter operates more exactly. Fig 29 and 30 shows the gate pulse & switching sequences of the Q1 and Q2 switches. The pulses to the switches are automatically generated by the PWM generator that is proportional to the reference voltage level. The switch voltage and switch current follows smoothly in this converter. For the auxiliary switch Q2, the negative peak current is controlled, so the circulating energy can be reduced and the stress of the switch in higher rating loads can be restricted to the minimum level. The switch current and switch voltage for the switch Q1 and Q2 are detail in the fig 31 and 32. From the fig 31 and 32, it is clearly understood that the Q1and Q2

switches are operates under the ZCS condition. The switch Q2 shares the stress of the Q1 switch, and helps to improve the overall efficiency of the system to the power expected level of range.
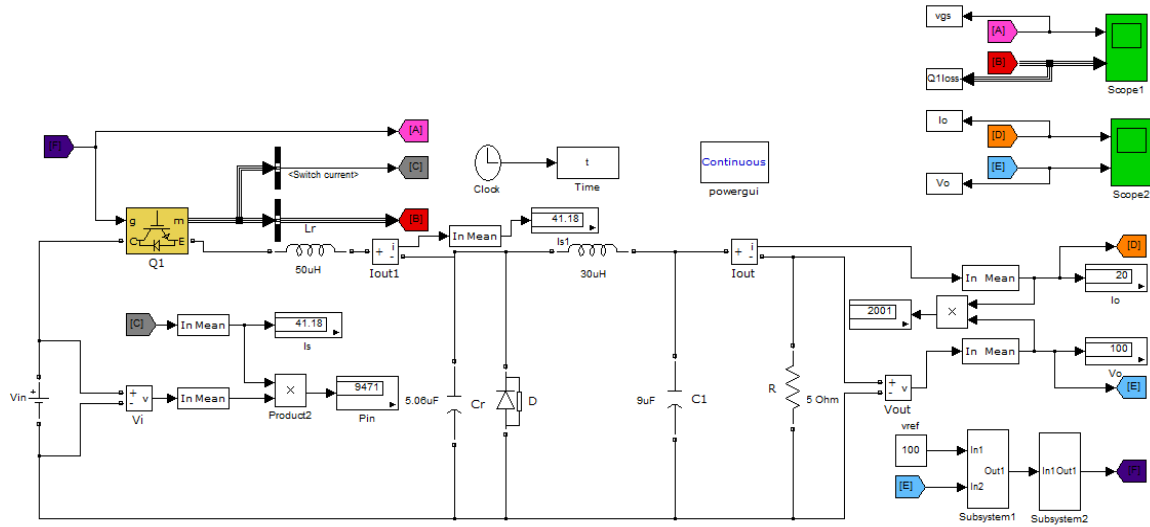

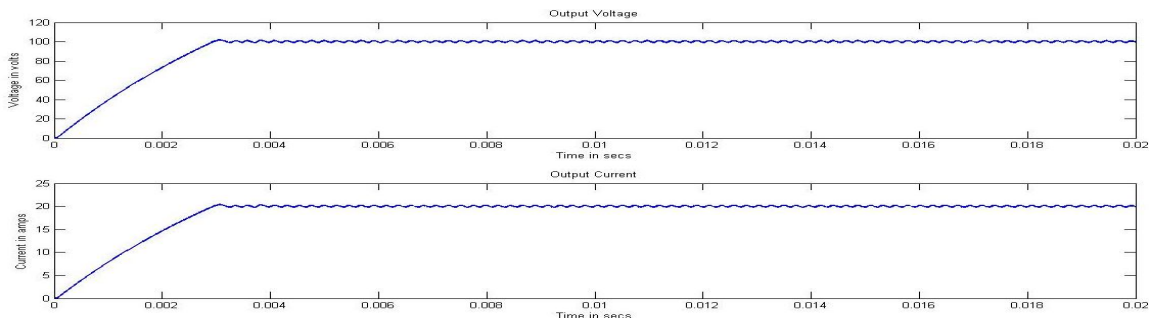Fig. 24 Simulation circuit of ZCS PWM buck converter in closed loop

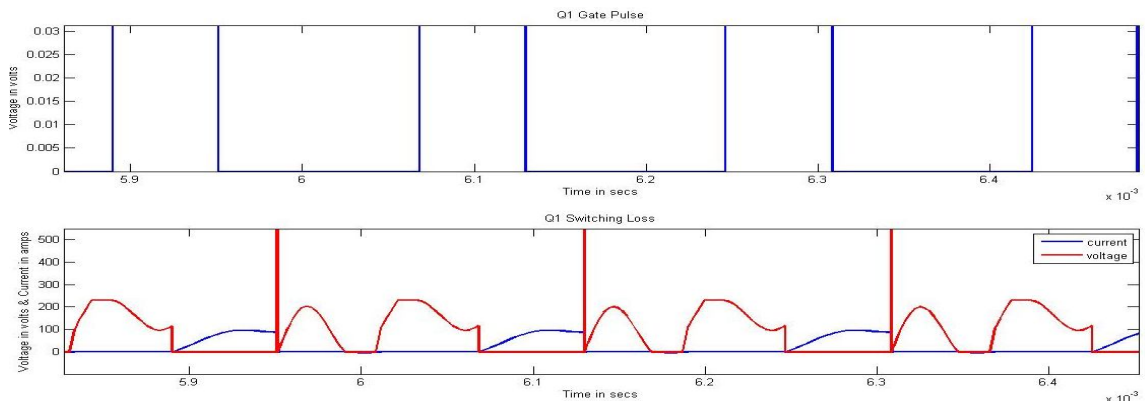Fig. 25 ZCS PWM buck output (voltage & current) in closed loop

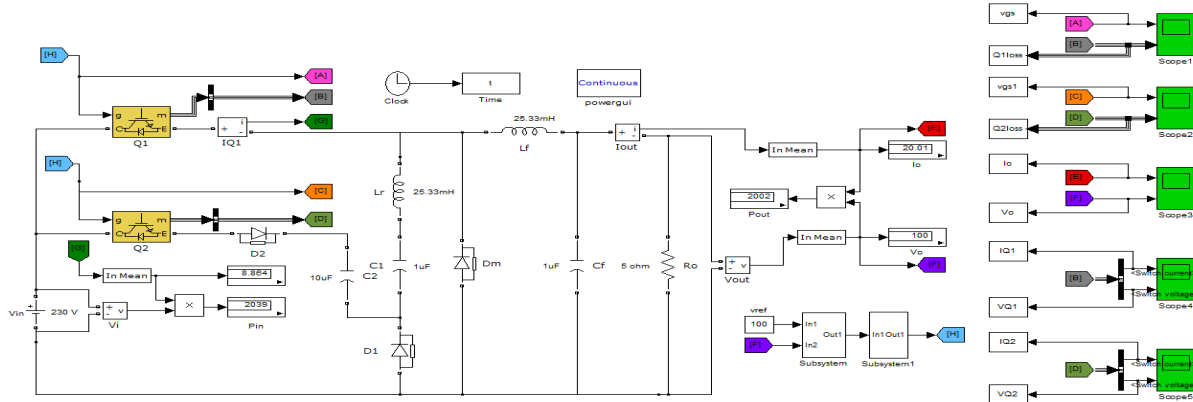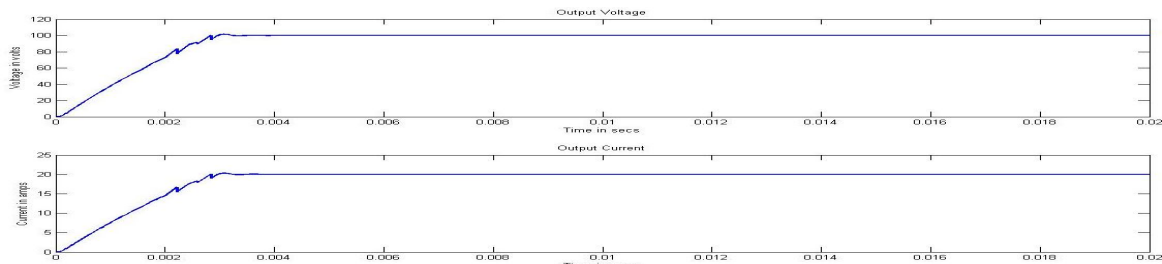Fig. 26 ZCS PWM buck Q1 (gate pulse & switching signal) in closed loop

Fig.27 Simulation circuit of ZCT PWM buck converter with hard switched auxiliary circuit in closed loop

Fig.28 ZCT1 PWM buck output (voltage & current) in closed loop
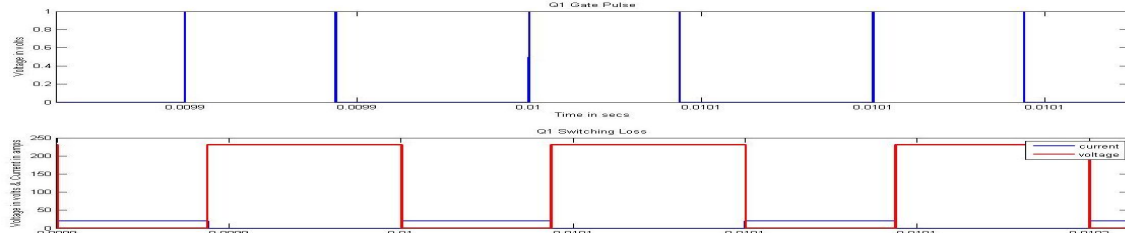
Fig. 29 ZCT1 PWM buck Q1 (gate pulse& switching signal) in closed loop

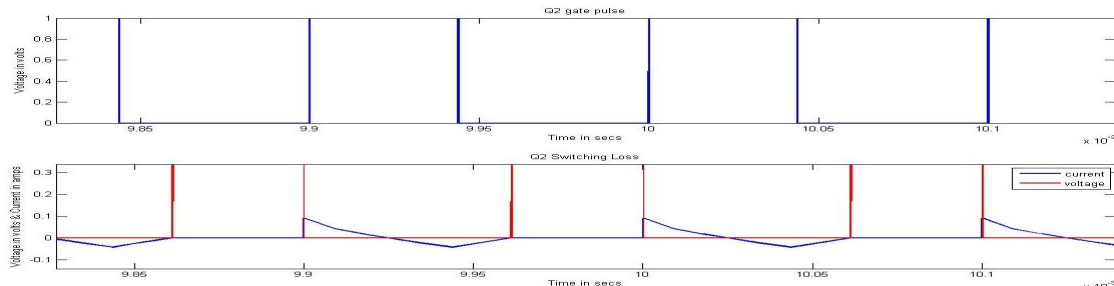
Fig.30 ZCT1 PWM buck Q2 (gate pulse& switching signal) in closed loop

5.3. ZCT PWM Converter with Soft Switching Auxiliary Circuit in Closed Loop Simulation

Simulation of the ZCT PWM converter with soft switching auxiliary circuit is shown in fig 35. An important think has to be noted here that powergui is selected as discrete and sampling time is 0.1µs. Because while selecting the continuous powergui the simulation hits consecutive zero crossings, to improve the performance of the simulation no way other than selecting the discrete powergui. The converter generates more close to the reference voltage as the output voltage. For this type of soft switched converters, even there is no requirement for the closed

loop control, because by applying the proper duty cycle we could achieve the exact output power that needed for the applications. The respective output voltage and output current for the converter is shown in fig 36. The output voltage and output current has some small levels of oscillations from its reference value, probably 0.5% of voltage and current, because the simulation was carried out under the discrete environment. Also there is no way to simulate this converter in continuous powergui mode.
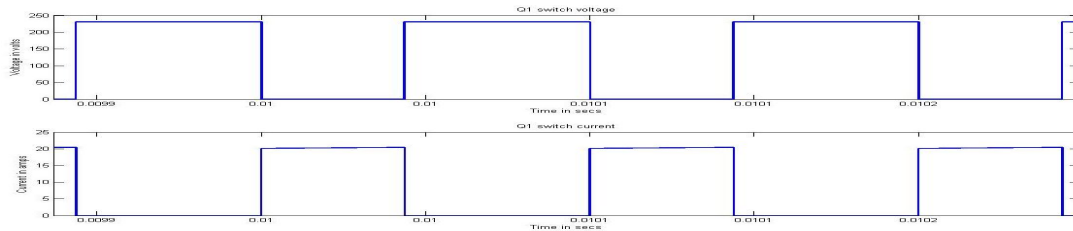

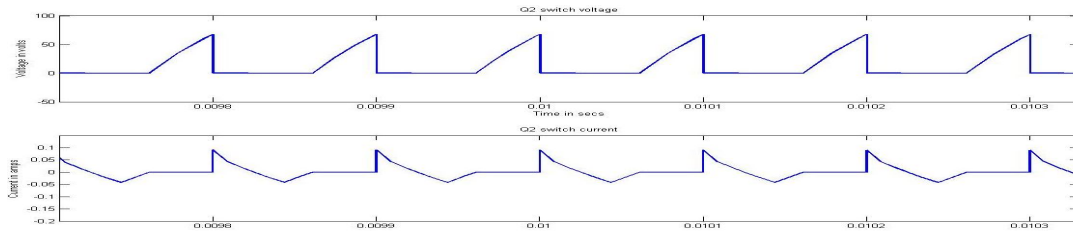Fig. 31 ZCT1 PWM buck Q1switch (voltage & current) in closed loop

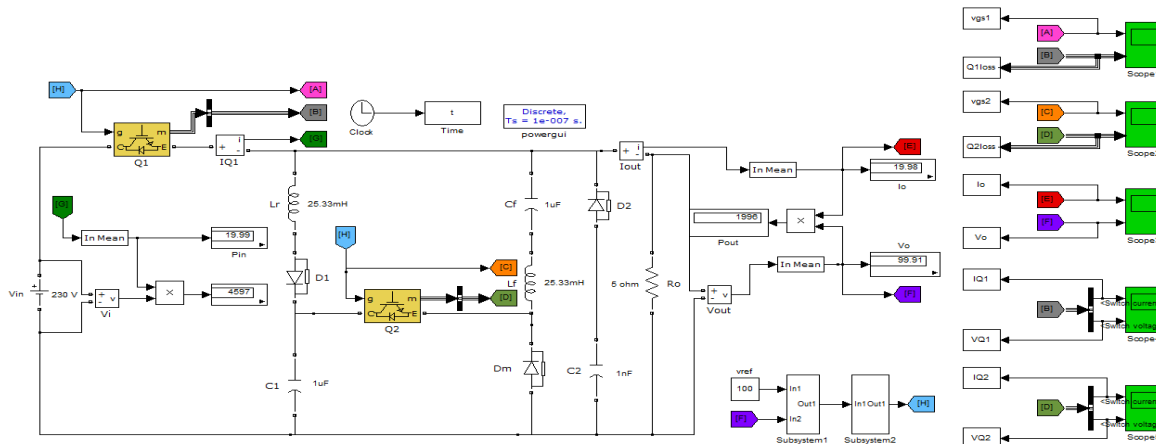Fig.32 ZCT1 PWM buck Q2 switch (voltage & current) in closed loop

Fig.33 Simulation circuit of ZCT PWM buck converter with soft switched auxiliary circuit in closed loop

The continuous powergui generally has the more accuracy. The converter shown in fig 33 can be simulated only for a three cycle in continuous powergui integrator simulation, after a three cycle the simulation hits 1000 consecutive zero crossings. So only for a small time period this simulation is possible in continuous integral simulation. Therefore for the better performance the discrete time powergui has been selected. Simulation results for gate pulse and switching signal of the Q1 & Q2 switch for the ZCT PWM with soft switching auxiliary circuit had shown in fig 35 &36.
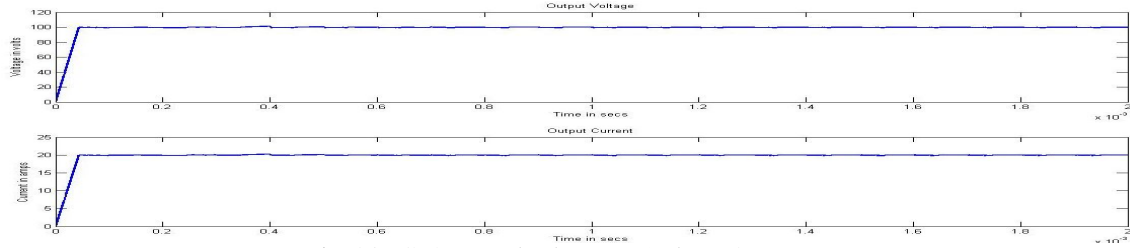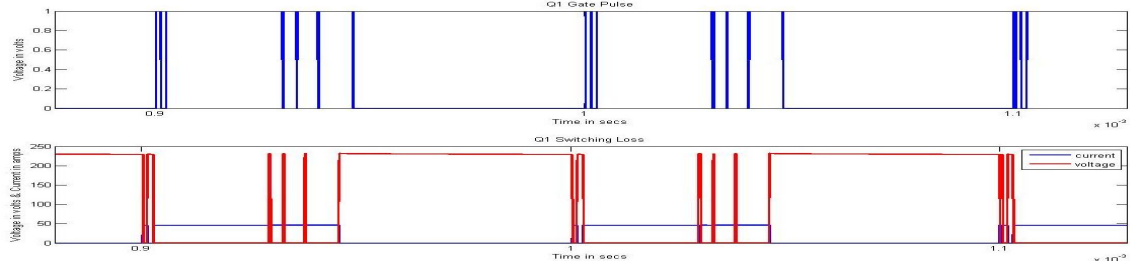
Fig. 34 ZCT2 PWM buck output (voltage & current)

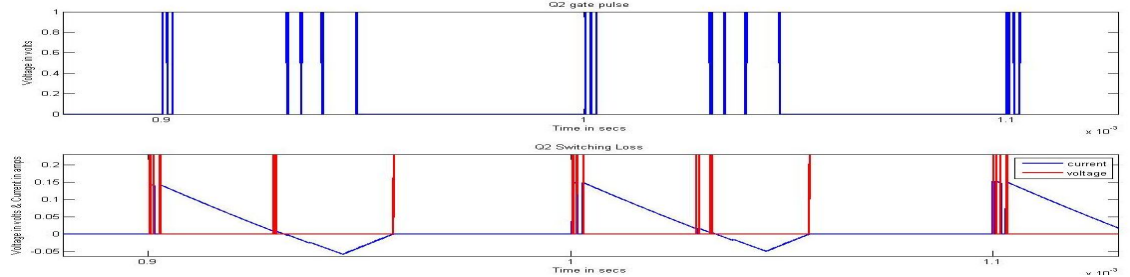Fig.35 ZCT2 PWM buck Q1 (gate pulse &switching signal) in closed loop

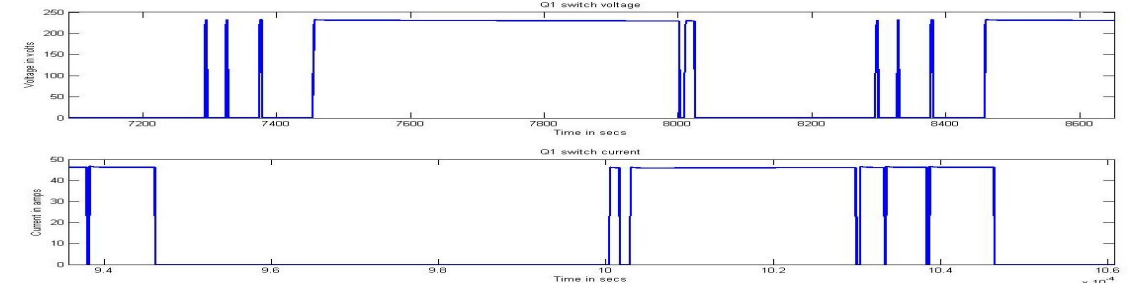Fig.36 ZCT2 PWM buck Q2 (gate pulse &switching signal) in closed loop

Fig. 37 ZCT2 PWM buck Q1switch (voltage & current) in closed loop

The Q1, Q2 switches are operating under the ZCS condition. It is the automatically generated pulse and switching sequences for the closed loop simulation. This results could be generated for only this much of accuracy because the different integral environment from the previously simulated results. The switch voltage and switch current individually shown in fig 37 and 38 for the converter shown in fig 33. The main and auxiliary switch continuously conducts, to exactly reach the reference voltage level. The switch voltage has the large time period and magnitude value in this discrete integrator simulation process. Even the Q1, Q2 switches are having only one vector dimensional in simulation while plotting it in the command window.
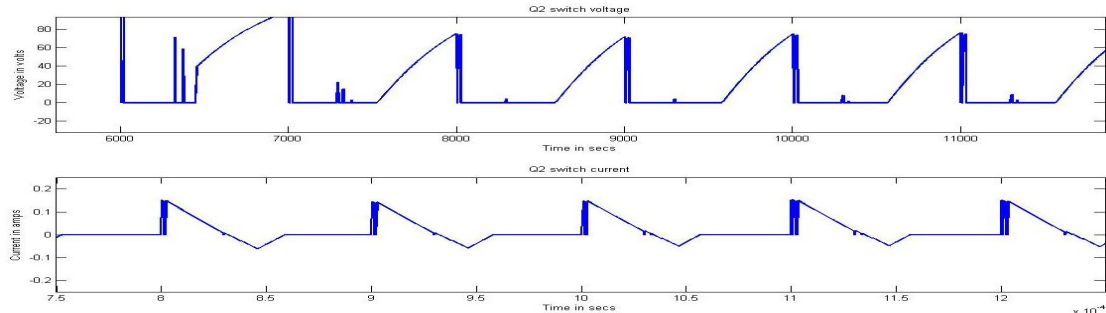
Fig. 38 ZCT2 PWM buck Q2switch (voltage & current) in closed loop

VI. CONCLUSION

An improved two types of soft switched low stress ZCT PWM buck converter is designed, according to the test result the main and auxiliary switch in the proposed converters is turned on and turned off, correspondingly at zero current, and also all the components are operating under soft switching to reduce the voltage/current stress caused by the input voltage of the resonant capacitor. So the power dissipation is reduced in the switch. The result of the proposed ZCT PWM buck converters are compared with the results of the conventional ZCS PWM buck converter, and is found that the switching losses are reduced and improved efficiency in the ZCT PWM converters than the conventional ZCT PWM converters. Also a closed loop approach in the MATLAB simulink has been designed, for both the ZCS and ZCT PWM buck converters.

REFERENCES

[1] Siddhartha Nigam, Pramit Baul, Sourabh Kumar "Soft Switched Low Stress High Efficient ZVT PWM DC-DC Converter For Renewable Energy Applications" 978-1-4673-6150-7/13/2013 IEEE Transaction.

[2] G. Hua, E. X. Yang, Y. Jiang, and F. C. Lee, "Novel zero current-transition PWM converters," IEEE Trans. Power Electron, vol. 9, no. 6, pp. 601–606, Nov. 1994.

[3] H. Bodur, A.F Bakan "An Improved ZCT PWM converters for high power applications,"IEEE Trans. Ind. Appl., vol. 51, no.1. Feb 2004.

[4] Milan M. jovanovic "resonant, quasi-resonant, multi-resonant and soft switching PWM techniques - merits and limitations". International Journal of Electronic, 1994, VOL.77, NO. 5, 537-554

[5] P. Das and G. Moschopoulos, "A zero-current-transition converter with reduced auxiliary circuit losses," in *Proc*. IEEE INTELEC, 2005, pp. 545–550.

[6] P. Das and G.Moschopoulos, "A Comparative Study of Zero-Current-Transition PWM Converters," in IEEE Transactions on industrial electronics, vol. 54, no. 3, June 2007.

[7] E.Adib and H.Farzanehfard, "Family of Zero-Current Transition PWM Converters," in IEEE transactions on industrial electronics, vol. 55, no. 8, august 2008.

[8] M. Prathap Raju, A. Jaya Lakshmi, "Soft switched DC-DC PWM Converters," IJERT, Vol. 1 Issue 6, August – 2012.

[9] N.Mohan, M.undeland, W.P. Robbins, "Power Electronics Converters, Applications and Design," Third edition, Wiley India.

[10] P.S. Bimbhra, "Power Electronics," Fifth edition, Khanna Publishers, India.

BIOGRAPHY

P.Sankar is working as an Asst. Prof in CSI College of Engineering, Department of Electrical and Electronics Engineering, The Nilgiris, Tamilnadu, India. He obtained his B.E degree in Electrical Engineering from Karunya University, Coimbatore, Tamilnadu, India in the year of 2000, and M.E degree in 2006 from the same institution. He has over 10 years of teaching experience and his area of research is in soft switching and renewable energy.

R.Jegatheesan received his B.E degree in Electronics and Communication Engineering in 2012 from Karpaga Vinayaga College of Engineering and Technology, affiliated to Anna University Chennai, Tamilnadu, India and he is currently doing his M.E degree in Power Electronics and Drives in CSI College of Engineering, The Nilgiris, Tamilnadu, India affiliated to Anna University Chennai.